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Soil crumbling during tillage as a function of soil organic matter content

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A b s t r a c t. The soils from England, France and Poland having a range of organic matter contents were studied. The total contents of clay and organic matter are used to calculate the amounts of non-complexed clay and organic matter in the soils. Measurements of soil water retention are used to calculate the values of an index of soil physical quality, *S**. It is shown that soils with larger contents of non-complexed clay have smaller values of *S** whereas soils with larger contents of non-complexed organic matter have larger values of *S**. We then use these values of *S** in an existing model based on results from tillage experiments in the field to predict the amount of soil crumbling produced by mouldboard ploughing. It is predicted that soils with larger contents of organic matter will crumble into smaller aggregates (and fewer clods) when tilled. A new measure of non-complexed material, *NCM*, is introduced that enables different soils that are poor and rich in organic matter to be considered on the same scale.

K e y w o r d s: soil physical quality, organic matter, non-complexed material, mouldboard ploughing, direct drilling, pasture

INTRODUCTION

It is well known that organic matter is a 'good thing' in soil and that it 'improves' it. However, there is very limited information available about the effects of soil organic matter on soil/machine interactions. In this paper, we present predictions for the size distribution of clods and aggregates produced by tillage of soils having different contents of organic matter.

The ideal seedbed has been described as having aggregates < 5 mm diameter (Braunack and Dexter, 1989; Dexter, 1988; Russell, 1973). On the other hand, clods *ie* large aggregates are considered to be a problem because they make the soil more heterogeneous and uneven. Here, we define clods as aggregates larger than 50 mm diameter.

The aim of this work was to use of existing models to predict the soil break-up during tillage, and to examine the effects of soil organic matter content on the amount of small aggregates and clods produced during tillage.

This is done in three steps: firstly, we use the measured clay and organic matter contents of the soils to calculate the contents of non-complexed clay (for soils with small organic matter contents) or non-complexed organic matter (for soils with large contents of organic matter). Secondly, we use measured results for the soil water retention in an existing theory to obtain values of the index of soil physical quality, *S** (Dexter, 2004). We then apply these results in an existing empirical model for the soil crumbling that occurs during mouldboard ploughing. This gives us predictions of the size distributions of aggregates produced as a function of the content of organic matter.

We note that all of the results used in this work were obtained using either undisturbed soil samples measured in the laboratory or real soil in real fields tilled with real mouldboard ploughs.

MATERIALS AND METHODS

Soil samples were collected from fields in England, France and Poland that contained “old” experimental plots (more than 25 years old). The English soils were collected from the Highfield experiment at Rothamsted Research Station at Harpenden (about 35 km north of the centre of London). The French soils were collected from Boigneville (about 60 km south of the centre of Paris at the Arvalis-Institut du Végétal). The Polish soils were from Grabów (about 20 km west from Puławy).

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With the English soil, 5 treatments were measured:
- permanent fallow (which has been cultivated several times each year to kill weeds),
- permanent cereals (which has been cropped annually with cereals since 1949),
- rotation (this site has been maintained since 1949 in a 3 year grass-clover + 3 year cereal rotation),
- re-seeded grass (this plot was ploughed initially in 1948 and reseeded with grass shortly afterwards),
- permanent grass (this is the original, unbroken grassland that used to cover the entire field).

With the French soil, the treatments were started in 1970. Two treatments were measured:
- tilled (this involves mouldboard ploughing annually to a depth of 25 cm),
- direct drilled (in this treatment, the soil is disturbed only in the seed row to about 5 cm depth).

In both treatments, the crop rotation is wheat – maize.

With the Polish soil, an experiment on crop rotations and fertilization was sampled. The experiments were started in about 1975. Two treatments were measured:
- low inputs of organic matter (the crop rotation is: potatoes, winter wheat, spring barley and maize),
- high inputs of organic matter (the crop rotation is potatoes, winter wheat + mustard, spring barley + clover, and red clover + grass). Farm-yard manure was added before the potato phase.

Both treatments had conventional tillage with mouldboard ploughing.

The particle size distributions of the soils were measured by the sedimentation (hydrometer) method. The contents of organic carbon were measured by wet oxidation.

The water retention characteristics of the soils were measured using standard methods. These involved drying soil samples from saturation to a range of pore water suctions on sand tables with hanging water columns and in ceramic pressure plate extractors. The range of pore water suctions, h, applied was from 10 hPa to 15 000 hPa. This range corresponds to $pF1.0$ to $pF4.2$ where pF is defined as the logarithm (base 10) of the pore water suction in hPa. For the French soils, samples were also equilibrated over saturated solutions of KCl, NaCl, NaBr, $MgCl_2$ and LiCl to give values of pF = 5.34, 5.58, 5.85, 6.18 and 6.47, respectively.

Tillage was done over a range of water contents in the field in Hungary and in Sweden. Large samples of tilled soil were analysed by sieving. The results were expressed as the proportions by mass of clods > 50 mm diameter for the Hungarian soils and proportions > 50, >10 and >5 mm diameter for the Swedish soils. Details of the field experiments have been published previously (Dexter and Birkás, 2004; Keller *et al*., 2007).

Crop residues, when incorporated into soil, become decomposed by microbes to form the soil organic matter. This comprises humic acids and a range of other compounds. The soil organic matter (*OM*) interacts with the clay particles (< 2 μm) to form a complex that is relatively stable in water. It has been found that unit amount (by mass) of organic carbon (*OC*) forms a complex with m = 10 units of clay (Dexter *et al*., 2008). In this paper, we assume that *OM* = 1.724 *OC*.

If the soil has a small content of *OC* (or *OM*), then all the *OC* will be complexed and some of clay will not be complexed. On the other hand, if the soil has a large content of *OC*, then all of the clay will be complexed but not all of the *OC* will be complexed. To distinguish between these possibilities, algorithms are necessary because continuous functions are not possible.

The amount of complexed organic carbon, *COC,* can be calculated for each soil using the following algorithm:

$$COC = if\left[OC < \frac{clay}{m}\right] then\,[OC]\; else\left[\frac{clay}{m}\right], \qquad (1)$$

and the amount of non-complexed organic carbon, *NCOC*, using:

$$NCOC = if\left[(C - COC) > 0\right] then\left[C - COC\right] else\,[0]. \qquad (2)$$

It is possible to quantify the amounts of complexed and non-complexed clay in a similar way to the amounts of complexed and non-complexed carbon given by Eqs (1) and (2), above. The amount of complexed clay, *CC*, is given by:

$$CC = if\,[mOC < clay]\; then\,[mOC]\; else\,[clay], \qquad (3)$$

and the amount of non-complexed clay, *NCC*, is given by

$$NCC = if\,[(clay - CC) > 0]\; then\,[clay - CC]\; else\,[0]. \qquad (4)$$

The complex (*COC* + *CC*) is relatively stable in water, has a low density and is important in controlling several valuable soil physical properties (Dexter *et al*., 2008). The *NCOC* is associated with soil hydrophobicity (or non-wetting behaviour) as found by de Jonge *et al.* (2009). The *NCC* is associated with the soil content of readily-dispersible clay, *RDC,* (Dexter *et al.,* 2008). *RDC* is associated with the instability of soil in water and the hard-setting phenomenon.

The water retention data, measured as described above, in the range of $1.0 < pF < 4.2$ were fitted to the Groenevelt and Grant (2004) equation:

$$w = k_1\left[\exp\left(\frac{-k_0}{(pF_0)^n}\right)\right] - \exp\left(\frac{-k_0}{(pF)^n}\right), \qquad (5)$$

in which k_1, k_0 and n are adjustable parameters. This equation has a sound basis in thermodynamic theory (Groenevelt and Bolt, 1972; Groenevelt and Grant, 2004) and is for systems in thermodynamic equilibrium. Additionally, for the French soils, the values of water content obtained over saturated salt solutions were included in the curve fitting. Eq. (5) states that the water content will be zero at pF_0. The value of pF_0 has been determined by the authors to be 6.65 (Dexter *et al*., 2011). Equation (5) gives the water content at saturation as:

$$w_{sat} = k_1 \left[\exp\left(\frac{-k_0}{(pF0)^n} \right) \right], \tag{6}$$

Equation (5) has an inflection point (a point where the curvature = zero) at:

$$pF_i = \left[\frac{nk_0}{(n+1)} \right]^{1/n}, \tag{7}$$

$$w_i = k_1 \left[\exp\left(\frac{-k_0}{(pF0)^n} \right) - \exp\left(\frac{-(n+1)}{n} \right) \right]. \tag{8}$$

The curve of w plotted against pF has a slope at the inflection point given by:

$$\frac{dw}{d(pF)} = -k_1 \left[\exp \frac{-(n+1)}{n} \right] nk_0 \left[\frac{n+1}{nk_0} \right]^{((n+1)/n)}. \tag{9}$$

The slope at the inflection point when w is plotted against $ln(h)$ has been used as an index of soil physical quality, S. In previous work, S was calculated from fitted parameters of the van Genuchten (1980) water retention equation. In this present study, the slope is calculated from the fitted parameters of the Groenevelt and Grant (2004) equation, as in Eq. (9) above. This procedure gives slightly different values for the slope at the inflection point which we designate S^*:

$$S^* = \frac{-1}{\ln(10)} \frac{dw}{d(pF)}. \tag{10}$$

In Eq. (10) the minus sign is added simply to make values of the index positive. There are only small difference in the values of S and S^* calculated as described above. When we compared the values obtained previously for 8 soils, we obtained:

$$S = 0.0029 + 0.954S^*, \quad r = 0.984, \; p < 0.0001 \tag{11}$$
$$(\pm 0.0030) \quad (\pm 0.070)$$

A fuller description of S and of the soil physical behaviour associated with different values of S is given in Dexter and Czyż (2007). For the present purposes, it is sufficient to know that values of $S > 0.035$ are associated with good soil physical properties whereas values of $S < 0.035$ are associated with poor soil physical properties. However, the changes in behaviour are progressive and there is no sudden change at $S = 0.035$. This value is empirical and is based on observations and experience of soil behaviour in the field. We have assumed that values of S and S^* are equivalent and that the same categories of soil behaviour are associated with the same values of S^*.

Tillage experiments were done in the field in Hungary (Dexter and Birkás, 2004) and in Sweden (Keller *et al*., 2007). Five different soils were used in Hungary and four different soils in Sweden. In these experiments, tillage by mouldboard ploughing was done over a range of different water contents. The structure of the resulting tilled soil was analyzed by sieving to obtain the size distribution of the aggregates and clods produced. Also, the values of the index S were obtained for these soils.

The results showed clearly that the water content given by Eq. (8) is the optimum water content for tillage. That is, tillage at this water content produces the minimum amount of clods (> 50 mm diameter) and the maximum amount of small aggregates. When tillage is done at the optimum water content, then the amounts of different sizes of aggregates produced may be estimated from Fig. 1. The results for clod production from Hungary and Sweden were almost identical even though the soils had very different genetic origins.

Here, we focus on the proportion, P(> x) of the tilled soil that is in the form of clods or aggregates (> x mm diameter) after tillage at the optimum soil water content.

RESULTS AND DISCUSSION

The compositions of the experimental soils are given in Table 1. The complexed and non-complexed components of the soil organic carbon and the clay as obtained using Eqs (1) to (4) are given in Table 2.

The parameters of the Groenevelt and Grant water retention equation, as obtained by non-linear curve fitting are given in Table 3. Calculated values of the index of soil physical quality, S^*, are also presented in Table 3. The water

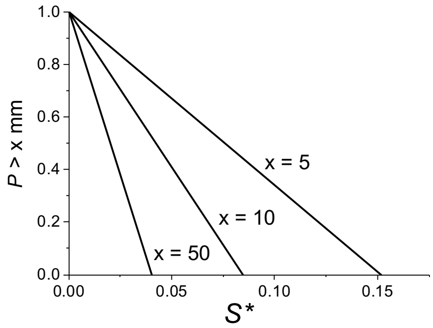

Fig. 1. Size distribution of aggregates produced by tillage as a function of S^* (Keller *et al*., 2007).

T a b l e 1. Compositions of the experimental soils

Site and treatment	Sand	Silt	Clay	Organic matter
	(g kg^{-1})			
England, Rothamsted				
Permanent fallow	90	670	240	19.0
Permanent cereals	130	630	240	26.0
Rotation	110	640	250	36.0
Re-seeded grass	110	630	260	48.0
Permanent grass	110	670	220	55.0
France, Boigneville				
Tilled	80	660	260	22.9
Direct-drilled	78	686	236	49.8
Poland, Grabów				
Low *OM* input	707	265	28	11.2
High *OM* input	722	255	23	13.5

T a b l e 2. Contents of organic carbon (*OC*), complexed organic carbon (*COC*), non-complexed organic carbon (*NCOC*), complexed clay (*CC*) and non-complexed clay (*NCC*)

Site and treatment	*OC*	*COC*	*NCOC*	*CC*	*NCC*
	(g kg^{-1})				
England, Rothamsted					
Permanent fallow	11	11	0	110	130
Permanent cereals	15	15	0	150	90
Rotation	21	21	0	210	40
Re-seeded grass	28	26	2	260	0
Permanent grass	32	22	10	220	0
France, Boigneville					
Tilled	13.3	13.3	0	133	127
Direct-drilled	28.9	23.6	5.3	236	0
Poland, Grabów					
Low *OM* input	6.5	2.8	3.7	28	0
High *OM* input	7.8	2.3	5.5	23	0

retention curve over the whole range of water contents from saturation to complete dryness for Boigneville B soil is shown in Fig. 2, as an example.

When we apply the values of S^* given in Table 3 to the results in Fig. 1, we obtain the predictions given in Table 4. The gives estimates of the proportions of different size ranges of aggregates obtained by tilling the different soils at their optimum water contents. It can be seen that, when the content of organic matter is higher, then the amounts of clods produced is smaller and the amounts of small aggregates produced is greater.

The lines in Fig. 1 that give the proportions of clods > x mm as a function of S^* are given by:

$$P(> 50 \text{ mm}) = 1.0\text{-}28.6\ S^*, \quad (12)$$

$$P(> 10 \text{ mm}) = 1.0\text{-}11.8\ S^*, \quad (13)$$

T a b l e 3. Parameters of the Groenevelt and Grant (2004) water retention equation (Eq. (5)) and values of the index of soil physical quality, S^*

Site and treatment	k_1	k_0	n	S^*
		England, Rothamsted		
Permanent fallow	2.5494	7.556	0.586	0.0203
Permanent cereals	3.0205	6.642	0.530	0.0233
Rotation	0.8456	5.578	0.887	0.0279
Re-seeded grass	1.0783	4.461	0.816	0.0391
Permanent grass	1.0480	4.555	0.844	0.0396
		France, Boigneville		
Tilled	0.6824	6.838	1.021	0.0246
Direct-drilled	0.4377	11.920	2.049	0.0474
		Poland, Grabów		
Low *OM* input	0.1849	12.418	2.588	0.0310
High *OM* input	0.2108	11.894	2.777	0.0406

T a b l e 4. Values of S^* and predicted proportions, $P(<x)$, of the soil in aggregates or clods smaller than x mm diameter after tillage by a single pass of a mouldboard plough at the optimum water content

Site and treatment	S^*	$P(<50)$	$P(<10)$	$P(<5)$
		England, Rothamsted		
Permanent fallow	2.5494	7.556	0.586	0.0203
Permanent cereals	3.0205	6.642	0.530	0.0233
Rotation	0.8456	5.578	0.887	0.0279
Re-seeded grass	1.0783	4.461	0.816	0.0391
Permanent grass	1.0480	4.555	0.844	0.0396
		France, Boigneville		
Tilled	0.6824	6.838	1.021	0.0246
Direct-drilled	0.4377	11.920	2.049	0.0474
		Poland, Grabów		
Low *OM* input	0.1849	12.418	2.588	0.0310
High *OM* input	0.2108	11.894	2.777	0.0406

$$P(> 5\text{ mm}) = 1.0\text{-}6.58\, S^*. \qquad (14)$$

We note that the proportion of small aggregates *eg* < x mm diameter is given by:

$$P(< x\text{ mm}) = 1\text{-}\, P(>x\text{ mm}). \qquad (15)$$

For example,

$$P(<5\text{ mm}) = 6.58\, S^*,\ \text{for values of } S^* < 0.15. \qquad (16)$$

Some predictions from the above equations are given in Table 4. As discussed in the introduction, a good seedbed should be composed of aggregates < 5 mm diameter. The results in Table 4 show that such a seedbed cannot be produced by a single pass of a mouldboard plough even when the soil is in good physical condition *ie* with a high value of S^*. This is consistent with experience and is the reason why secondary tillage *eg* with harrows is always performed.

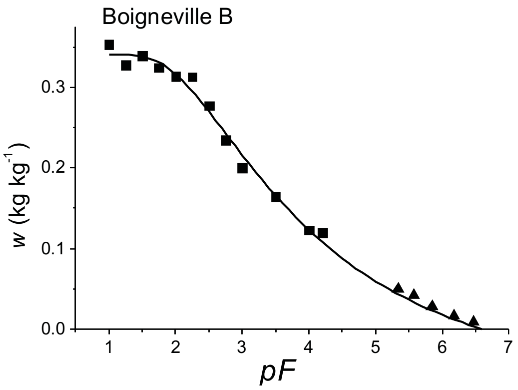

Fig. 2. Water retention curve for the Boigneville B soil. The points shown as squares were measured using pressure plate equipment, and the points shown as triangles were measured by equilibration over saturated salt solutions. The smooth curve is the fit to the Groenevelt and Grant (2004) equation.

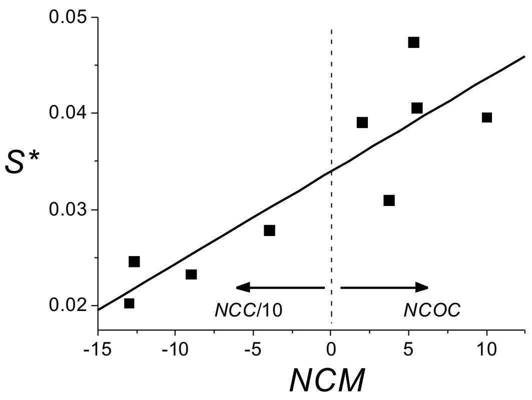

Fig. 3. Soil physical quality, S^*, as a function of non-complexed material, *NCM*.

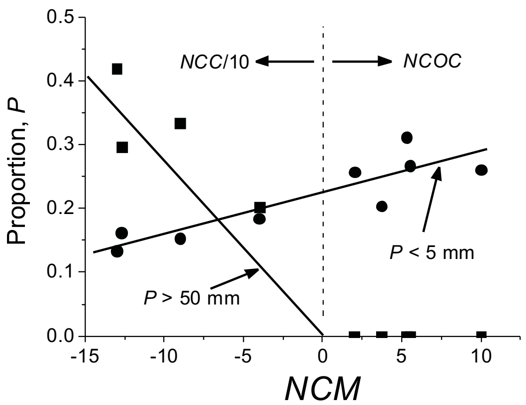

Fig. 4. Predicted proportions of clods (> 50 mm diameter) and small aggregates (< 5 mm diameter) produced as a function of the soil content of non-complexed material, *NCM*.

To study the effects of the amounts and types of non-complexed material, *NCM*, we have defined:

$$NCM = NCOC - NCC/10 \tag{17}$$

The value of 10 in Eq. (17) is the value of m in Eqs (1) to (4). It is needed here to put *NCOC* and *NCC* onto effectively the same numerical scale because *OC* has approximately 10 times the effect on soil physical properties as clay. The effect of *NCM* on S^* is shown in Fig. 3. The regression equation is

$$S^* = 0.034 + 0.00096NCM, \; r = 0.88, \; p < 0.002 \tag{18}$$

$$(\pm 0.002) \; (\pm 0.00019)$$

The value of S^* at the intercept (when $NCM = 0$) is given by Eq. (18) as $S^* = 0.034 \pm 0.002$ which is not significantly different from the empirical value of $S = 0.035$ for the boundary between 'good' and 'poor' soil physical quality as presented by Dexter (2004) and Dexter and Czyż (2007). At $NCM = 0$, all the clay and all the *OM* are complexed. We can see that negative values of *NCM* correspond with 'poor' soil physical quality whereas positive values of *NCM* correspond with 'good' soil physical quality.

We have used Eqs (12), (16), (17), (18) and the results in Table 2 to predict the proportions of clods (P>50 mm) and small aggregates (P<5 mm) produced by ploughing as a function of the soil content of non-complexed material, *NCM*, as defined in Eq. (17). These predictions are given in Fig. 4. The results for clods are consistent with the results in Fig. 1 and with the experimental results of Dexter and Birkás (2004) and Keller *et al.* (2007). The results for small aggregates show that a single pass of a mouldboard plough produces < 30% of small aggregates even with soil in the best physical condition.

CONCLUSIONS

1. The use of the new measure of non-complexed material, *NCM*, enables results for soils that are poor and rich in organic matter to be analyzed on the same rational basis and plotted on the same physical scale.

2. Values of *NCM* can be used to predict the amounts of clods (> 50 mm diameter) and aggregates (< 5 mm diameter) produced when soil is tilled at or close to the optimum water content for tillage. Clod production is predicted to be zero for values of $NCM > 0$.

3. The use of *NCM* values helps to explain soil responses to tillage. Negative values of *NCM* correspond to poor soil physical quality due to the presence of non-complexed clay, whereas positive values of *NCM* correspond to good soil physical quality due to absence of non-complexed clay and the presence of non-complexed organic matter.

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