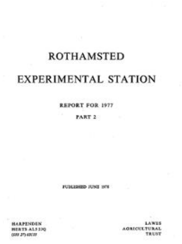
Rothamsted Experimental Station Report for 1977 Part 2


ROTHAMSTED
EXPERIMENTAL STATION
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PART 2

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Effects of Management and Manuring on Physical Properties of some Rothamsted and Woburn Soils

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R. J. B. Williams (1978) *Effects of Management and Manuring on Physical Properties of some Rothamsted and Woburn Soils ;* Rothamsted Experimental Station Report For 1977 Part 2, pp 37 - 54 **- DOI: https://doi.org/10.23637/ERADOC-1-36541**

Effects of Management and Manuring on Physical Properties of some Rothamsted and Woburn Soils

R. J. B. WILLIAMS

Introduction

Variation in soil mechanical composition at Rothamsted Farm is less than at Woburn. At Rothamsted, the soils belong mainly to the Batcombe series and are formed from 'various superficial and drift deposits, including Clay-with-flints, valley head gravels and alluvium, over Upper Chalk with nodules of flint'. The soils of Broadbalk Field and Barnfield have been described previously (Avery and Bullock, 1969; Avery *et al.*, 1972).

At Woburn Farm, the soils vary greatly from the loamy sands and sandy loams of the Cottenham and Stackyard series to the clay loams of the Evesham, Flitwick, and Rowsham series. The soils of the Great Hill area and of Lansome Field have been described (Catt *et al.*, 1975; 1977).

At both farms a variety of experimental treatments have produced soils with different organic matter contents. Soils under grass range from short leys to permanent pasture over 100 years old. Soils under arable crops range from those in recent rotations, to others that have received either no nutrients or regular annual applications of organic manures or fertilisers for over a century. Soils under woodland established for over 200 years can be compared with others allowed to revert to natural vegetation after long periods under arable management (Jenkinson, 1971; Garner, 1965), or with cultivated bare fallows started on both farms 17 years ago.

The physical behaviour of soils in the field that influences crop growth and ease of cultivation depends upon the complex interaction between weather and soil composition, particularly the amount and origin of the organic matter, and the particle size distribution of the mineral fraction, loosely described as 'texture'. Particle size distributions of a typical Rothamsted soil from Barnfield and of a lighter soil at Woburn from Stackyard Field are shown in Fig. 1, and illustrated by scanning electron micrographs in Plates 1a and 1b. The Rothamsted soil has little medium and fine sands in the 500–100 μm fractions that form the greater part of the Woburn soil in which the 200–250 μm fraction predominates. The Rothamsted soil has eight times as much coarse silt (20–50 μm) as the Woburn soil and more fine silt (2–20 μm), so that these two fractions combined in the Rothamsted soil account for about 50%, or double the average clay content. Even if the Rothamsted soil is heavily compacted in wet weather to form dense cloddy structures, it requires only a few cycles of wetting and drying, without frost action, to restore it to a good tilth. This is also true for subsoil brought to the surface by deep ploughing, which weathers and crumbles into small aggregates just as easily, indicating that much organic matter is not essential for the process. Plate 1a at the lower magnification shows fine cracks that coincide with the dimensions of these small aggregates. Free iron oxides, present in larger quantities in Clay-with-flint subsoils than in other British clay soils, may be responsible for this (Avery *et al.*, 1972).

The Stackyard soil contains about 10% clay and only small amounts of very fine sand and coarse silt (50–100 μm), suggesting that the stable pores between the larger sand grains (Plate 1b) are never completely filled with finer soil fractions. However, translocation of some of the finer fractions through the topsoil, or re-stratification due to erosion in wet weather, can result in the formation of layers of small porosity and large

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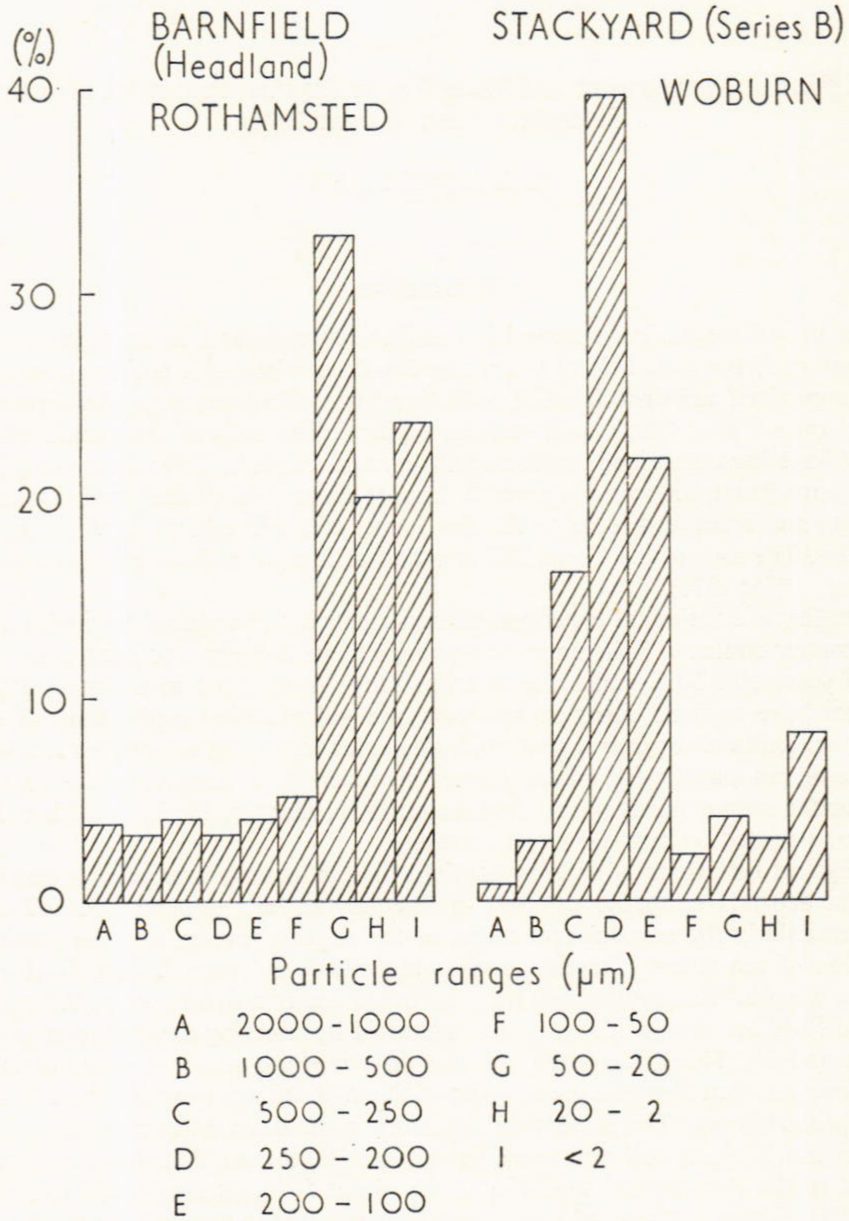

FIG. 1. Particle size distributions of Rothamsted and Woburn soils.

density that impede drainage, produce slurried topsoils and increase the transport of soil even on gentle slopes, as occurred in May 1973 on the similar soil on Butt Close (Catt *et al.*, 1975, Plate 4).

At Rothamsted, infiltration of surface water is rarely slow and surface capping does not interfere with seedling emergence. An example of a surface 'cap' that formed on Barnfield as the result of a total of 82 mm of intense rain is shown as scanning electron micrographs in Plate 2. The surface was composed mainly of closely packed grains of coarse silt size (20–50 μm). Soil just below the surface showed moderate-sized cavities that had been protected from the impact of large raindrops. The effects of mechanical

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compaction on two soils at Rothamsted and one at Woburn on the growth and establishment of barley and globe beet was reported by Kubota and Williams (1967). They were least on Pastures Field after an eight-year ley, more on Barnfield that contained little organic matter, and greatest on the soil of Stackyard Field at Woburn.

The influence of soil porosity upon the movement of soil organisms that damage crops has been discussed by Jones (1969 and 1975) who stated, 'it is probably significant that soils in which root ectoparasitic nematodes are abundant and troublesome usually contain more than 80% sand, less than 10% clay and little organic matter'. The sandy loams and loamy sands of the Stackyard and Cottenham series fall into that category and the incidence of nematode problems is greater there than at Rothamsted.

This paper describes the results of measurements of stability, strength, and density of four soil series and relationships of differences in their mechanical composition or organic matter content caused by management.

Methods

Most of the methods have been described previously (Williams and Cooke, 1961; Williams, 1971).

Soil preparation. About 2 kg of soil sampled 0–23 cm by spade in the field was dried in a current of air at room temperature. Suitable sized clods were removed for density determinations. The remainder of the sample was used to prepare 4–6 mm aggregates required for measurements of soil stability and strength and < 2 mm soil required for mechanical analysis, bulk density, water-holding capacity and chemical analyses.

Physical measurements

% Water Slaking Instability (I/WS). Measured by the change in volume of a column of 30 g air-dried aggregates (4–6 mm) held in a glass tube 13 mm internal diameter and about 40 cm long, when subjected to two cycles of flooding and draining; expressed as a percentage of the total possible loss in volume defined by the original volume of the column minus the particle volume of the soil aggregates used.

% Dry Mechanical Slaking Instability (I/DS). Measured by the change in volume of a column of air-dried aggregates 4–6 mm held in a metal tube 25 mm internal diameter and about 30 cm long when subjected to compaction at 7 kg cm^2 (100 psi) by a steel plunger for 1 min. The instability was calculated in the same manner as for I/WS.

% Total Mechanical Slaking Instability (I/MS). The total change in volume of the same column of aggregates used for Dry Mechanical Slaking when saturated by percolating water through the dry compacted column for 5 to 6 h, drained overnight and compressed in the same manner. The instability was calculated as for I/WS.

Breaking Strength (B/S). The load required to split a section (25 × 25 mm) of the compressed and air-dried cylinder produced by Total Mechanical Slaking. A polished steel penetrometer 12·5 mm diameter with a hemispherical tip was used.

% Water-Holding Capacity (WHC). 20 g of < 2 mm soil was saturated on a filter paper held in a 6 cm funnel by recycling the same 45 ml of water for several hours. The water absorbed after draining overnight was measured.

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***Bulk Density* (*BD*).** Using the apparatus described in the British Standard Specification No 1460 (1948) the density of 150 g of < 2 mm soil after tamping was determined.

Density of soil clods. Clods > 20 g obtained from the original air-dried field soil were oven-dried at 105°C and the apparent and specific densities measured by the method of Russell and Balcerek (1944).

Density of field soil by core sampling. A soil sampler described by Zwolinski and Rowe (1966) was used and the proportions of air, water, and solids by volume were calculated.

Chemical measurements

% Free calcium carbonate by the method of Williams (1948).

% Total nitrogen of soil dried at 105°C, by a Kjeldahl method (Bremner, 1960) using Cu and Se catalysts.

% Organic carbon by the method of Walkley & Black (1935) using < 0·5 mm soil. Results are reported without using the normal correction factor of 1·3.

Description of soils

Historical records of the Rothamsted soils extend to the early part of the seventeenth century when a map was made of the Manor of Rothamsted. This was discussed in the *Records of the Rothamsted Staff*, No. 5, June, 1935, when superimposition of the old field boundaries upon those shown on the Ordnance Survey map indicated that, although some fields had changed not only in name but also in their dimensions, parts of the farm have remained in arable cultivation (e.g. Broadbalk and Fosters Fields), under permanent pasture (Highfield and Great Field IV), or under natural vegetation (Manor and Knott Woods), for much of the time since 1623. Many soils listed in Appendix Table 1 have been subjected to changes involving experimental treatments within the last 100 years that have greatly altered their physical properties and nutrient contents.

The Woburn soils (Appendix Table 2) discussed here include those from Stackyard Field that had been in arable cultivation for over 100 years but were probably under permanent grass before 1840. The permanent grass on the Pightle was probably over a century old and that on Butt Furlong and Honey-Pot Field could be of similar age. Butt Close was mostly cultivated during the last century, Broad Mead, which has been cultivated since 1958, was previously under permanent grass. Amounts of free calcium carbonate in these soils are less than at Rothamsted.

Results

The location, treatment, mechanical composition, percentage of free calcium carbonate, organic carbon and total nitrogen of the soils on the Rothamsted farm (Appendix Table 1) and at Woburn (Appendix Table 2) are listed. The results of the physical measurements made on the soils from Broadbalk are given in Table 1, those for Rothamsted woodland soils in Table 2 and those for soils under grass or given large applications of organic manure are in Table 3. The results of measurements made on the cultivated bare fallows at both farms are in Table 4. Comparisons of measurement made on soils from the Rothamsted and Woburn Reference experiments are given in Tables 5 to 9. Yields and N contents of grass roots obtained from soils on the Woburn Reference

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Experiment after a long ley are in Table 10. Densities of soils from Stackyard Field at Woburn after erosion had occurred are given in Table 11.

Water slaking instability. Water slaking instability, although associated with soil mechanical composition and large for soils with little clay or organic matter, can be small in most soils under grass (Williams, 1971). Results for this measurement showed large variations for soils from both farms due to previous management. Soils under old grass or woodland on the Batcombe series (Highfield, Great Field IV, Broadbalk and Geescroft Wilderness, and the Manor and Knott Woods) at Rothamsted, and on the Cottenham series (Butt Furlong and the Pightle) or the Evesham series (Honey-Pot Field) at Woburn were all stable to water slaking (Tables 2 and 3).

Results for the soils on the Reference experiments (Widdowson and Penny, 1972; 1973) on both farms (Table 5) reflect not only differences in mechanical composition but also organic matter content due to previous management. The soils on the arable section of the Rothamsted Experiment (Williams, 1973) sited on old grassland contained, on average, about twice as much organic matter as those on old arable land at Woburn. There was no effect on instability from a one-year ley on the Rothamsted soil and additions of farmyard manure with or without fertilisers increased soil swelling properties, as indicated by negative values for this measurement. At Woburn the soil was completely stable under a long ley and stability was maintained by a short ley following a one-year arable break. Increases in stability under a one-year ley, following 15 years of arable cropping, were larger on soil receiving annual applications of fertilisers or manure; and the untreated soil was least stable. Similar but smaller effects were shown for soils after 14 years of arable cropping; an untreated soil was as unstable as a 17-year-old cultivated fallow, which contained less organic matter, in the same field (Table 4). The transient stability produced by leys on these light soils was shown for the soil on the Cottenham series on Butt Close (Table 3) a year after ploughing. Similar results have been reported previously (Williams, 1975).

Soils on the Batcombe series (Broadbalk Field) that had been under continuous wheat given only fertilisers since 1843 and in arable cultivation for much longer (Table 1), were

TABLE 1

Results of physical measurements on Broadbalk soils (Section One) 1977

Plot	Annual treatment	% Water slaking	% Mechanical slaking: Dry	% Mechanical slaking: Total (wet + dry)	Breaking strength (kg)	% WHC	BD <2mm soil (g ml⁻¹)	Oven-dried clod: BD (g ml⁻¹)	Oven-dried clod: Particle density (g ml⁻¹)	Oven-dried clod: % Total porosity
2	35 t ha⁻¹ FYM	0	12	57	7·7	62	1·23	1·58	2·46	36
3	No manures	24	14	60	13·3	51	1·29	1·63	2·50	36
5	PK fertilisers	14	11	56	12·3	49	1·29	1·70	2·57	33
7	NPK fertilisers	17	13	57	15·2	54	1·31	1·68	2·52	33
11	NP fertilisers	23	13	61	11·6	52	1·23	1·56	2·51	37
12	NPNa fertilisers	19	11	57	12.0	53	1·27	1·64	2·52	35

on average more stable than untreated soil or the 17-year-old fallows on Fosters Field. These soils were less stable than ploughed-up old pasture on Highfield which had been fallowed for the same length of time (Table 4). Annual applications of 35 t ha^{-1} of farmyard manure since 1843 completely stabilised arable soils on Broadbalk and Barnfield (Tables 1 and 4).

The relationship between water slaking instability and soil organic carbon (Fig. 2) shows that organic carbon was not related to instability in the arable soils from both

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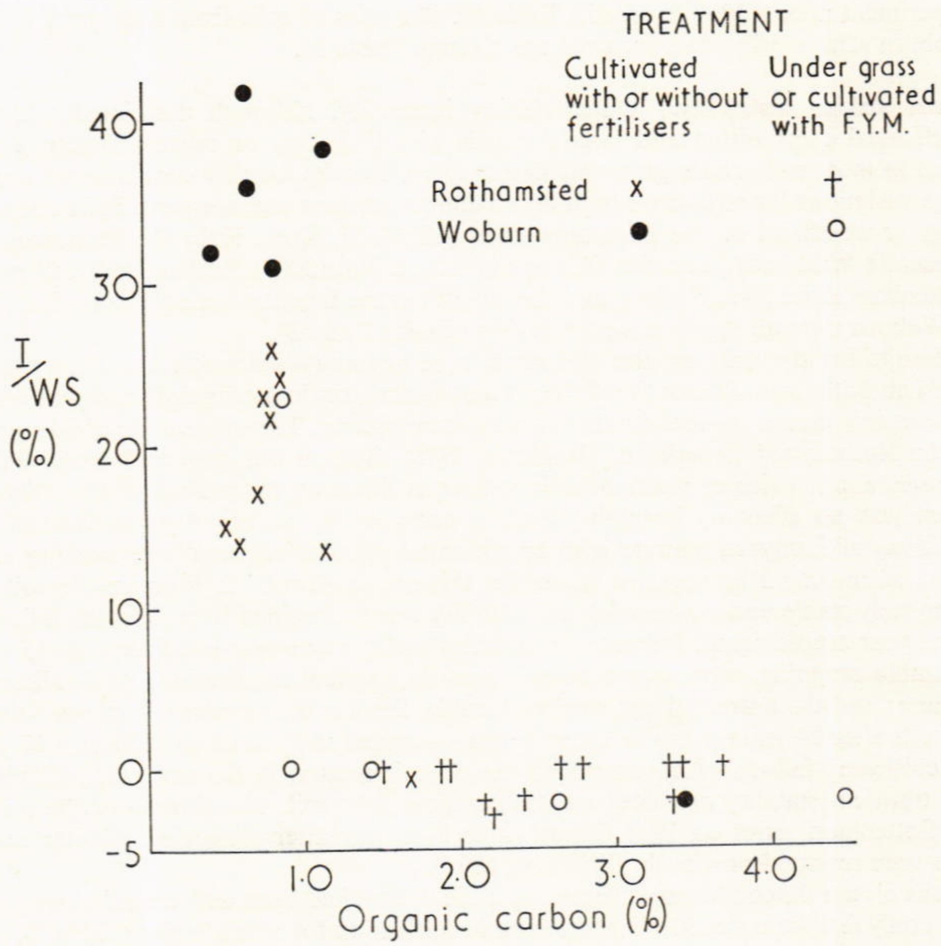

FIG. 2. Relationship between % water slaking instability (I/WS) and % organic carbon (Walkley & Black).

farms, provided that these soils were either untreated or had received only fertilisers. The Woburn arable soils were much more unstable than those at Rothamsted. Soils under permanent grass or long ley, or those that had received regular applications of manure were, with one exception, very stable, irrespective of texture or organic carbon content. The forms and distribution of soil organic matter that are responsible for stability are thus not adequately described by % organic carbon or total nitrogen, and further work is needed to clarify the function of different forms of organic matter on soil stability.

Dry mechanical slaking. Dry mechanical slaking, a measurement associated mainly with soil mechanical composition for soils of moderate organic matter content (Williams, 1971), varied from 8 to 23% for the soils from the Batcombe series at Rothamsted and the Evesham series at Woburn but most results were between 10 and 15%. Values for the lighter soils of the Cottenham and Stackyard series at Woburn were larger and varied from 25 to 41%. Smallest values obtained for the two sections of the Broadbalk Wilderness under grass (Table 2); were less than for soils from the wooded section at the same site, from Geescroft Wilderness of the same age, and under much older natural vegetation in the Manor and Knott Woods. Dry mechanical slaking was similar (10 – 15%) for unmanured soils on Broadbalk Field, under pasture on Highfield, under old

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TABLE 2

Results of physical measurements on woodland soils at Rothamsted

Site	% Water slaking	% Mechanical slaking: Dry	% Mechanical slaking: Total (wet + dry)	Breaking strength (kg)	% WHC	BD < 2 mm soil (g ml⁻¹)	Oven-dried clod: BD (g ml⁻¹)	Oven-dried clod: Particle density (g ml⁻¹)	Oven-dried clod: % Total porosity
Broadbalk Wilderness									
Wooded section	−2	14	58	11·4	88	0·93	1·41	2·45	42
Stubbed section	0	8	51	14·3	80	1·04	1·57	2·47	36
Grazed section	0	9	44	12·5	93	0·97	1·50	2·43	38
Geescroft Wilderness	0	18	57	11·8	44	1·25	1·57	2·41	35
Manor Wood	−3	16	55	6·7	71	1·19	1·36	2·32	41
Knott Wood	0	17	50	9·6	69	1·15	1·55	2·36	35

grass or in arable soils from Great Field IV, on fallowed soils from Barnfield, Fosters and Highfield, and on the Evesham series at Woburn (Broad Mead and Honey Pot Fields) (Tables 1, 3, and 4), although their organic matter contents differed greatly. The lighter soils on the Cottenham and Stackyard series at Woburn were, on average, three to four times as easily compacted when dry as the Rothamsted soils that contained much more clay (Tables 3 and 4). Soils under leys, or in arable cultivation on the Stackyard series that had received farmyard manure (Table 5), were less easily compacted when dry than the same soil in arable cropping without organic manure.

TABLE 3

Results of physical measurements on Rothamsted and Woburn soils with histories under grass or of long-term manuring

Site	% Water slaking	% Mechanical slaking: Dry	% Mechanical slaking: Total (wet + dry)	Breaking strength (kg)	% WHC	BD < 2 mm soil (g ml⁻¹)	Oven-dried clods: BD (g ml⁻¹)	Oven-dried clods: Particle density (g ml⁻¹)	Oven-dried clods: % Total porosity
Rothamsted									
Highfield									
Permanent pasture	0·0	12	34	9·1	84	0·97	1·39	2·42	44
Great Field IV									
Permanent grass	−1·8	14	49	15·2	82	1·03	1·24	2·42	49
Barnfield									
(Series 0. Plot 10)	0·0	23	57	9·8	62	1·37	1·64	2·36	30
Manor walled garden	0·0	18	59	4·1	63	1·09	1·35	2·27	41
Woburn									
Butt Furlong									
Permanent grass	0·0	34	62	1·5	48	1·33	1·67	2·47	32
Butt Close	37·6	32	63	1·9	39	1·30	1·58	2·61	39
Pightle									
Permanent grass	−2·2	26	43	0·7	67	1·12	1·35	2·41	44
Honey-Pot Field									
Permanent grass	−2·1	11	47	10·6	86	1·21	1·69	2·22	24
Broad Mead	−2·3	11	46	7·5	74	1·31	1·86	2·30	19

Total mechanical slaking. The range of values for total mechanical slaking, a measurement inversely related more to soil organic matter, particularly for grassland soils, than to clay content (Williams 1971), was large at Rothamsted and Woburn where the results varied from 34 to 62% and from 43 to 71% respectively. At Rothamsted, the smallest value was obtained for the soil under very old grass on Highfield and largest for a

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TABLE 4

Results of physical measurements on cultivated bare fallows at Rothamsted and Woburn

Site	Sampled	% Water slaking	% Mechanical slaking: Dry	% Mechanical slaking: Total (dry + wet)	Breaking strength (kg)	% WHC	BD <2 mm soil (g ml⁻¹)	Oven-dried clods: BD (g ml⁻¹)	Oven-dried clods: Particle density (g ml⁻¹)	Oven-dried clods: % Total porosity
					Rothamsted					
Fosters Field Old permanent fallow	1962	29	17	61	9·7	39	1·34	—	—	—
	1971	28	14	58	9·1	54	1·20	—	—	—
	1975	24	16	62	13·8	59	1·23	1·76	2·55	31
	1977	22	13	57	10·1	50	1·29	1·68	2·56	34
Fosters Field New permanent fallow	1975	14	14	59	11·2	60	1·34	1·58	2·47	36
	1977	26	15	62	11·9	49	1·29	1·58	2·53	38
Highfield Permanent bare fallow	1962	14	16	63	9·2	59	1·23	—	—	—
	1971	22	19	58	6·7	68	1·19	—	—	—
	1975	17	16	58	11·0	64	1·21	1·70	2·48	32
	1977	11	11	53	12·0	51	1·27	1·65	2·53	35
Barnfield Headland	1962	15	15	58	10·7	46	1·29	1·87	2·60	28
					Woburn					
Stackyard Permanent bare fallow	1962	40	26	65	4·9	27	1·34	—	—	—
	1971	35	29	65	2·9	48	1·39	—	—	—
	1975	36	26	63	3·5	41	1·40	1·81	2·58	30
	1977	32	26	69	8·6	37	1·44	1·74	2·56	32

TABLE 5

Water slaking instability and dry mechanical slaking instability of soils cropped and fertilised differently

Rothamsted and Woburn Reference experiments, 1973–76

Previous cropping	% Water slaking instability: Nil	Fertilisers	FYM	FYM + fertilisers	Mean	% Dry mechanical slaking: Nil	Fertilisers	FYM	FYM + fertilisers	Mean
				Rothamsted						
Potatoes	0·0	−0·3	0·0	−1·1	0·4	10·9	8·3	9·2	9·5	9·5
Kale	0·0	−1·1	−2·8	−1·2	−1·3	8·5	9·2	9·0	8·9	8·9
Winter wheat	0·0	0·0	−2·2	−1·3	0·9	9·2	10·5	10·6	10·4	10·2
Spring barley	0·0	−0·6	−2·2	−2·3	−1·3	14·5	14·6	12·5	14·8	14·1
Clover/Grass ley	0·0	−0·3	−2·6	−1·3	−1·1	12·0	9·0	8·1	10·3	9·9
Mean of all croppings	0·0	−0·5	−2·0	−1·4	−1·0	11·0	10·3	9·9	10·8	10·5
				Woburn						
14 years ley	0·0	0·0	0·0	0·0	0·0	23·9	26·4	22·4	27·8	25·1
14 years ley + 1 year arable + 1 year ley	0·0	0·0	0·0	0·0	0·0	31·1	30·8	28·5	32·9	30·8
15 years arable + 1 year ley	21·4	4·2	0·0	1·3	6·7	26·0	28·8	30·7	31·3	29·2
14 years arable	36·3	31·1	22·8	3·1	23·3	40·8	36·1	30·5	34·3	35·4

fallowed soil on Fosters Field. Similar results (50–57%) were obtained for soils from Geescroft Wilderness and the Manor and Knott Woods. The soil on Broadbalk Wilderness under grazed grass was less easily compacted than the ungrazed section (Table 2). The section that had reverted to woodland in 1886 was just as easily compacted as the

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soils under continuous wheat since 1843 in the nearby field (Table 1). Soils on the Rothamsted Reference Experiment that had received farmyard manure with or without fertilisers (especially if applied in the year of sampling) were less easily compacted when saturated, than the untreated soils or those receiving fertilisers only (Table 6). The clay loams of the Evesham series at Woburn behaved similarly to those at Rothamsted. The lighter soil on the Pightle gave a value 20% less than soil from Butt Furlong (Table 3), which was also under grass but containing about half the organic matter. These values were 13% less than on soils under a 14-year ley on the Reference Experiment on Stackyard Field (Table 6) that had total mechanical slaking values similar to the continuously

TABLE 6

Total mechanical slaking instability and particle densities of oven-dried clods of soil cropped and fertilised differently

Rothamsted and Woburn Reference experiments 1973–76

	%Total mechanical slaking					Particle density (g ml^{-1}) of oven-dried clods				
	Treatment					Treatment				
Previous cropping	Nil	Ferti-lisers	FYM	FYM+ fertilisers	Mean	Nil	Ferti-lisers	FYM	FYM+ fertilisers	Mean
	Rothamsted									
Potatoes	47·1	55·6	35·3	41·9	45·0	2·40	2·41	2·41	2·40	2·41
Kale	56·9	59·0	36·3	43·1	48·8	2·48	2·43	2·33	2·37	2·40
Winter wheat	61·9	60·3	48·9	51·6	55·7	2·46	2·43	2·38	2·36	2·41
Spring barley	65·3	63·9	54·7	53·1	59·3	2·40	2·48	2·38	2·40	2·42
Clover/Grass ley	64·6	55·4	41·5	43·4	51·2	2·40	2·37	2·39	2·37	2·38
Mean of all croppings	59·2	58·8	43·3	46·6	52·0	2·43	2·42	2·38	2·38	2·40
	Woburn									
14 years ley	57·3	60·3	49·3	55·9	55·7	2·41	2·46	2·40	2·28	2·39
14 years ley + 1 year arable + 1 year ley	66·9	57·7	57·3	60·4	60·6	2·51	2·50	2·44	2·44	2·47
15 years arable + 1 year ley	59·0	59·0	63·1	55·3	59·1	2·54	2·52	2·47	2·47	2·50
14 years arable	71·3	66·5	61·0	63·5	65·6	2·49	2·43	2·46	2·41	2·44

fallowed soil on the same field. As soil organic matter diminishes after old grassland is ploughed up it is well known that the resistance to compaction of the disturbed soil also declines and this is accompanied by an increase in surface slaking and capping due to rain. The results for the soil on the Batcombe series under pasture and fallowed for 17 years (Tables 3 and 4) indicate the magnitude of these changes for old grassland, and those on the same series (Table 6) the effect of a one-year ley. Results for permanent grass and ploughed up ley on the lighter soils of the Cottenham series at Woburn (Butt Close and the Pightle) (Table 3) were similar but the effect of compaction on diminishing soil porosity would be less on these soils than at Rothamsted due to the different packing characteristics of the soil particles present.

Breaking strength. Breaking strength of soil cylinders formed by total mechanical slaking, a measurement largely dependent on soil mechanical composition, is inversely related to dry mechanical slaking and increases with clay content (Williams, 1971). Smaller values are, however, found for soils containing much organic matter, irrespective of texture.

Results for the Rothamsted soils and the clay loams at Woburn varied from 4·1 to 16·4 kg and averaged about 11 kg, with smallest values (4·1–9·8 kg) obtained for the

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heavily manured soils on Broadbalk, Barnfield, Manor Garden, Knott and Manor Woods, and under old pasture on Highfield. Breaking strength of the soils from the Cottenham and Stackyard series at Woburn were smaller (0·7–8·6) and averaged 3·3 kg. Annual applications of farmyard manure for over 130 years to a cultivated soil on the Batcombe series (Broadbalk Field) were more effective in diminishing soil breaking strength than nearly twice as much organic matter in undisturbed soil on land allowed to revert to natural vegetation for over 90 years (Tables 1 and 2). Annual applications of farmyard manure for 20 years to soils on the same series under arable crops, following old grassland, decreased soil breaking strength by about 15% compared with the same soil untreated (Table 8). Fallowing old pasture on the Batcombe series increased soil breaking strength to a value similar to that of old arable land on the same series (Tables 3 and 4). Fallowing an old arable soil on the sandy loam of the Stackyard series for the same period increased soil breaking strength to a value similar to that on old pasture on the clay loams of the Batcombe series or on soil recently ploughed out of old grass

TABLE 7

Bulk density ($g\ ml^{-1}$) of < 2 mm soil and of oven-dried clods of soils cropped and fertilised differently

Rothamsted and Woburn Reference experiments, 1973–76

	Bulk density (< 2 mm soil)					Bulk density (oven-dried clods)				
	Treatment					Treatment				
Previous cropping	Nil	Ferti-lisers	FYM	FYM+ fertilisers	Mean	Nil	Ferti-lisers	FYM	FYM+ fertilisers	Mean
					Rothamsted					
Potatoes	1·09	1·17	1·17	1·12	1·14	1·49	1·46	1·51	1·43	1·47
Kale	1·22	1·22	1·18	1·14	1·19	1·56	1·44	1·35	1·44	1·45
Winter wheat	1·17	1·18	1·15	1·15	1·16	1·54	1·51	1·45	1·49	1·50
Spring barley	1·23	1·15	1·13	1·11	1·16	1·56	1·48	1·43	1·44	1·48
Clover/Grass ley	1·17	1·16	1·19	1·07	1·15	1·42	1·44	1·43	1·45	1·44
Mean of all croppings	1·18	1·18	1·16	1·12	1·16	1·51	1·47	1·43	1·45	1·47
					Woburn					
14 years ley	1·22	1·21	1·22	1·19	1·21	1·52	1·57	1·46	1·45	1·50
14 years ley + 1 year arable + 1 year ley	1·22	1·24	1·24	1·19	1·22	1·51	1·51	1·51	1·40	1·48
15 years arable + 1 year ley	1·27	1·27	1·27	1·25	1·27	1·61	1·60	1·55	1·55	1·58
14 years arable	1·31	1·34	1·31	1·31	1·32	1·59	1·52	1·49	1·53	1·53

on the Evesham series (Tables 3 and 4). Soils on the Stackyard series under arable cropping were about twice as strong when no farmyard manure had been applied but the range of values (2·3–4·5 kg) was small. Corresponding soils under a 14-year ley had slightly smaller breaking strength (Table 8).

Water-holding capacity. This measurement, closely related to soil organic matter content, especially under grass (Williams, 1971), varied greatly on the Batcombe series at Rothamsted (44–93%) where soil mechanical composition is very similar but organic carbon varied widely (Appendix Table 1). The largest value was obtained on the grazed section of Broadbalk Wilderness where the results for the wooded and 'stubbed' areas greatly exceeded those for soils under much older natural vegetation in the Manor and Knott Woods or for Geescroft Wilderness of same age that had the smallest value for water-holding capacity of all the Rothamsted soils measured. Soils under continuous

https://doi.org/10.23637/ERADOC-1-16

TABLE 8

Breaking strength and water-holding capacity (< 2 mm soil) of soils cropped and fertilised differently

Rothamsted and Woburn Reference experiment, 1973–76

	Breaking strength (kg)					% Water-holding capacity				
	Treatment					Treatment				
Previous cropping	Nil	Fertilisers	FYM	FYM+ fertilisers	Mean	Nil	Fertilisers	FYM	FYM+ fertilisers	Mean
				Rothamsted						
Potatoes	17·5	15·3	15·7	11·5	15·0	69	67	67	72	69
Kale	22·5	17·8	12·8	14·6	16·9	62	64	72	71	67
Winter wheat	14·0	14·5	13·2	11·7	13·4	67	69	70	71	69
Spring barley	11·6	13·1	12·9	10·7	12·1	67	63	62	69	65
Clover/Grass ley	16·6	18·7	15·5	14·3	16·3	67	70	73	73	71
Mean of all croppings	16·4	15·9	14·0	12·6	14·7	66	67	69	71	68
				Woburn						
14 years ley	3·3	3·3	2·1	2·1	2·7	55	60	62	65	60
14 years ley + 1 year arable + 1 year ley	3·3	2·3	4·2	2·5	3·1	54	53	54	55	54
15 years arable + 1 year ley	7·1	5·8	5·7	4·5	5·8	47	49	53	52	50
14 years arable	4·2	4·5	2·4	2·3	3·4	47	44	46	48	46

wheat on Broadbalk that had received fertilisers had, on average, 36% less water-holding capacity than the wooded section on the adjacent Wilderness. Annual dressings of 35 t ha^{-1} of farmyard manure for 134 years decreased this difference by 10%. Soils under old grass (Highfield and Great Field IV) had larger water-holding capacities than similar soils when fallowed or under arable cropping. After 17 years of fallow on Highfield, water-holding capacity had decreased by 30% from that under old pasture to that on fallow of same age on Fosters Field and little more than on the headland of Barnfield that had been cultivated and largely uncropped for more than a century. Water-holding capacities of the soils from the Rothamsted Reference experiment (Great Field IV) were little different as the result of cropping or applications of fertilisers and manure. This was probably the effect of residual organic matter from old grassland on which the experiment was sited and differs from the effect of leys in increasing the water-holding capacity of the Stackyard series soil at Woburn, that initially contained much less organic matter (Appendix Table 2 and Table 8), by an average of 14% compared with soils under arable cropping. For the other soils at Woburn the clay loams on the Evesham series had similar water-holding capacities to those at Rothamsted with similar organic matter. For the lighter soils on the Cottenham and Stackyard series, water-holding capacity was very closely related to organic matter with the largest value (67%) obtained for the loamy sand on the Pightle and 30% less for the fallowed sandy loam on Stackyard.

Water-holding capacity of soils on the Batcombe series at Rothamsted was less closely related to soil organic matter than those on the Cottenham, Stackyard, and Evesham series at Woburn. Soils under woodland had a larger range of values but the mean value was less than under permanent grass.

Soil density

Bulk density of < 2 mm soil measured using the method described in BS. 1460 (1948) is more closely related to soil organic matter than to mechanical composition (Williams, 1971). It also shows a general relationship with the density of soil clods. On the Rothamsted soils on the Batcombe series and those at Woburn on the Cottenham and Stackyard

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series containing less than 13% of clay (Appendix Tables 1 and 2), the density of < 2 mm soil varied from 0·93 to 1·37 g ml^{-1} and 1·12 to 1·44 g ml^{-1} respectively.

Soils on Broadbalk Wilderness that were under arable cultivation long before 1886, but have reverted to natural vegetation since, contained much organic matter and had smaller densities (Table 2) than soils on Geescroft Wilderness of the same age or the cultivated arable soils on Broadbalk Field that had grown continuous wheat since 1843 (Table 1). The soil under old pasture on Highfield (Table 3) had the same density as that on the grazed section of Broadbalk Wilderness, but when cultivated and fallowed for 17 years, had a similar density to that on the fallow of same age on the old arable soil on Fosters Field. In contrast, on the soils on the arable rotation of the Rothamsted Reference experiment on Great Field IV differences in density of < 2 mm soil (Table 7) were less, and the effect of farmyard manure applied with or without fertilisers was small because of the better maintenance of organic matter derived from permanent grass on which this experiment was sited 20 years before.

On the Woburn Reference experiment on Stackyard Field densities of <2 mm soil under a 14-year ley were less than when this soil was under arable crops for the same period but the effect of farmyard manure was negligible. The smallest density (1·12 g ml^{-1}) of all of the Woburn soils was measured on the loamy sand on the Pightle that contained less than 10% clay and 2·6% organic carbon and the largest (1·44 g ml^{-1}) on the continuously fallowed sandy loam soil on Stackyard Field that contained 13% clay but only 0·4% organic carbon.

Density of clods of Rothamsted soils varied from 1·24 to 1·87 g ml^{-1} and at Woburn from 1·35 to 1·86 g ml^{-1} for bulk density. Particle density at both sites varied from 2·30 to 2·60 g ml^{-1}.

At Rothamsted, largest clod densities were measured on the cultivated and fallowed soils on Highfield, Fosters Field and Barnfield (Table 4) and on the soils of the Continuous Wheat Experiment on Broadbalk (Table 1) that had not received farmyard manure. Much smaller densities were measured for the soils that contained more organic matter on Broadbalk Wilderness, Manor and Knott Woods (Table 2), and under permanent grass on Highfield and Great Field IV (Table 3).

A similar relationship existed between cultivated and grassland soils on the Cottenham and Stackyard series at Woburn; the smallest clod density was measured on loamy sand on the Pightle and the largest on fallowed soil from Stackyard Field. The clay loams belonging to the Evesham series at Woburn had large clod densities although they contained much organic matter from long periods under grass.

Density of soil cores were measured on three treatments after 14 years of arable cropping or long ley on the Reference Experiment on Stackyard Field at Woburn (Table 9). Other measurements were made on topsoils and subsoils after erosion by rain on the same field (Table 11).

On the Reference experiment, smaller densities at each depth were found for the soils that had received NPK fertilisers and where root action by larger crops could have increased soil porosity. The subsoils (28 to 31 cm) under long ley, without applied N, had the largest density (1·63 g ml^{-1}). Under ley receiving NPK fertilisers it was less (1·53 g ml^{-1}). Treatments that had received NPK fertilisers contained less moisture at each depth measured than untreated soil. For any treatment, there was less water and more air-filled space under arable conditions than in undisturbed soil under the long ley. Grass roots penetrate only shallowly on this soil compared with arable crops. Some estimates of grass roots and their N contents on an 'ash-free' basis, obtained by dry sieving from this experiment are shown in Table 10. These are less than reported by

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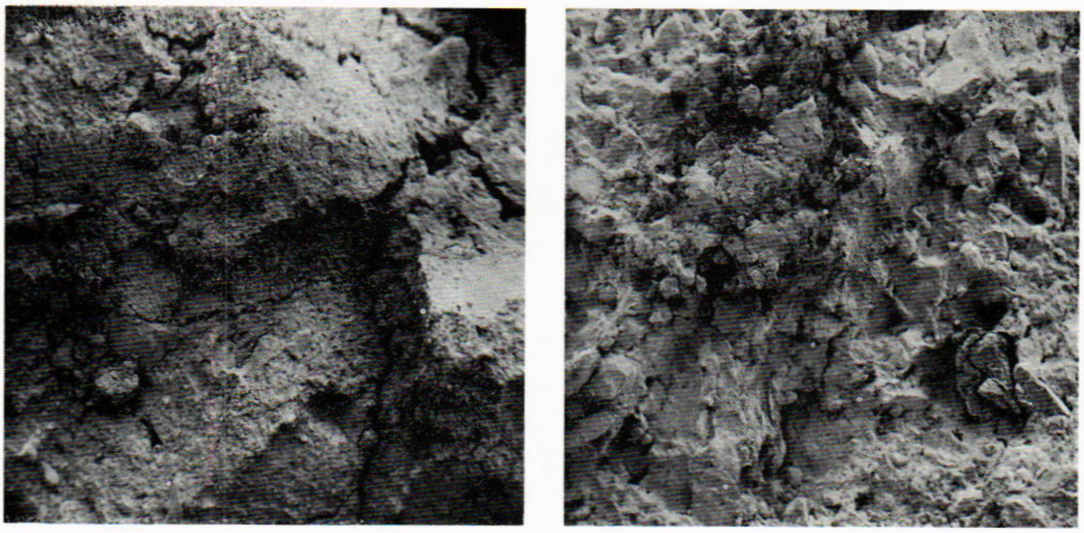

×24 ×240

(a) Barnfield, Rothamsted.

×24 ×240

(b) Stackyard Field, Woburn.

PLATE 1. Scanning electron micrographs of topsoils.

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PLATE 2. Scanning electron micrographs of soil 'cap' on Barnfield, Rothamsted (June 1973) ($\times$240). Top. Surface of 'cap'. Bottom. Lateral view just below 'cap'.

TABLE 9

Bulk densities of cores from topsoils on the Reference experiment Stackyard Field, Woburn, October 1971

Plot	Treatment	Depth (cm)	Bulk density (g ml^{-1})	Soil composition (% v/v) Soil	Water	Air
			After 14 years ley			
52	Nil	8–10	1·38	53	26	21
		20–23	1·53	59	25	16
		28–31	1·63	63	22	15
55	PK	8–10	1·51	58	26	16
		20–23	1·54	59	21	20
		28–31	1·63	62	19	19
54	NPK	8–10	1·49	57	22	21
		20–23	1·51	58	17	25
		28–31	1·53	59	11	30
			After 14 years arable cropping			
25	Nil	8–10	1·52	59	21	20
		20–23	1·45	56	18	26
		28–31	1·59	61	14	25
35	PK	8–10	1·50	58	23	19
		20–23	1·49	58	16	26
		28–31	1·54	59	15	26
27	NPK	8–10	1·38	53	19	28
		20–23	1·37	53	12	35
		28–31	1·48	57	8	35

TABLE 10

Yields of oven-dried roots (0–15 cm) and contents of total N after 14 years' ley Woburn Reference experiment, Stackyard Field, 1973

Treatment	Oven-dried roots* (t ha^{-1})	N content (kg ha^{-1})
Unmanured	4·8	58·6
PK fertilisers	5·0	76·3
NPK fertilisers	5·5	75·3
FYM	4·4	65·9
FYM + NPK fertilisers	5·9	120·0

* Calculated on an 'ash free' basis

Mattingly (1974) for grass roots extracted by wet sieving from the nearby Organic Manuring experiment following a seven-year ley, but show, on a comparative basis, that an extra tonne per hectare of 'ash-free' roots was present in the soil that had received farmyard manure and fertilisers and contained twice as much total nitrogen as the roots of unmanured grass.

Section One of Stackyard Field had been in arable cultivation for at least 130 years and organic matter was small (Appendix Table 2). Densities were measured in the topsoil and subsoil above and below a plough 'pan' formed at 20 cm (Table 11). This soil showed no signs of implement compaction at the surface. Soil density was least at the surface but increased at a depth of 10 cm, decreasing slightly at the depth of the 'pan' and below it. At 10 cm the wet soil contained only 3% of air-filled pore space. On a nearby area there were large differences in the density of cores taken below and to the side of wheelings left by implements, with values greater than 1·80 g ml^{-1} at 10 cm depth beneath wheelings, compared with about 1·7 g ml^{-1} outside them. Soil moistures in this area were almost uniform but air-filled pore space varied from 6 to 17%. Under

https://doi.org/10.23637/ERADOC-1-16

TABLE 11

Bulk densities of cores of eroded soils at Woburn Experimental Station Stackyard Field, November, 1971

Location	Depth (cm)	Bulk density (g ml^{-1})	Soil composition (% v/v) Soil	Water	Air
Section I. Continuous arable (130 years)					
Surface soil	3	1·58	60	26	14
Compacted layer	10	1·78	68	29	3
Plough pan	20	1·70	65	27	8
Subsoil below pan	30	1·68	64	25	11
Outside tractor wheeling—Surface soil	3	1·49	56	27	17
—Plough layer	10	1·69	65	25	10
Inside tractor wheeling —Surface soil	3	1·61	62	26	12
—Plough layer	10	1·82	69	25	6
Section II. Newly sown ley (Sept. 1971)					
—Surface	3	1·66	63	34	3
—Plough layer	10	1·77	66	28	6
—Plough pan	20	1·70	65	24	11
12-year grass headland between 1 and II	3	1·70	65	23	12
Section III. Residual phosphate experiment site					
—Slurried surface soil	3	1·65	63	33	4
—Plough pan	20	1·85	70	26	4
—Subsoil below pan	36	1·63	62	30	8

a recently sown ley on Section II the soil down to 20 cm was very compact with densities varying from 1·66 to 1·77 g ml^{-1}. Soil under older grass on the adjacent headland had a similar surface density.

Sheet erosion occurred in 1971 on Section II and surface water had collected on the site of the Residual Phosphate experiment (Stackyard series I, Section III). Here the soil had been converted into a slurry due to the restricted entry of water into a plough 'pan' formed at 20 cm. Core samples taken from this site showed that the density of the 'pan' was large (1·85 g ml^{-1}) but that below it the soil was much less dense (1·63 g ml^{-1}) and had a porosity 8% greater. The surface soil contained a third of its volume of water that, on this very sandy soil (Appendix Table 2), transformed it into the readily erodable material mentioned above. Although these soils had been drastically altered by compaction or erosion, all had some residual air-filled pore space.

Soil density is frequently used as a measure of soil compaction that is in turn linked with soil structure, the most important agricultural property of which is the amount and distribution of pores within a soil and the ability of these to retain adequate water and air for good crop growth. The concept of limiting density in soils (1·75 g ml^{-1} for sands and 1·63 g ml^{-1} for clays) that could cause root impedence was introduced by Veihmeyer and Hendrickson (1948) and concerned bulk densities at which, in most soils, there are insufficient pores of the right sizes to enable plant roots to ramify efficiently. Soil density is changed by large increases in organic carbon that also increases not only water-holding capacity but soil fertility. For the soils used here, that contained a wide range of organic matter contents, large differences in density of soil crumbs and clods were obtained for soils that had been subjected to contrasting management, that either greatly increased or decreased soil organic matter by lack of cultivation or frequent fallowing. At Rothamsted, on the Batcombe series, growing wheat for over 130 years did not greatly change the total porosity of clods removed from the topsoil from that found for soil under grazed grass on the same land that had been uncultivated for about 90 years (Tables 1 and 2), or on an old arable soil that had been fallowed for 17 years (Table 4). Smaller densities, and consequently larger total porosities, were obtained for soils under old pasture on the same soil series but these rapidly decreased on fallowing to values similar to those on cultivated soils.

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Soils in arable rotations on the widely different Batcombe and Stackyard series (Table 7) showed little variation in the density of < 2 mm soil or clods; as the result of similar treatments at each site. Total porosity of clods on both series exceeded 35% and most clod densities were less than 1·6. However, at Woburn on the Stackyard series, where grass roots do not penetrate deeply, compaction under a long ley produced subsoil densities, measured by soil cores, that exceeded 1·6 g ml^{-1} and which were larger than under arable crops on the same experiment. This emphasises the need for subsoiling on this land after long periods under grass.

Compaction of this soil by implements and pan formation produced core densities >1·8 g ml^{-1} that impede root penetration. Erosion of topsoils, resulting from slow infiltration through dense layers of soil after heavy rain, is responsible for changes in the distribution of soil particles and the consequent movement of adsorbed nutrients.

Summary

Measurements of water and mechanical slaking, breaking strength, water-holding capacity and density were made on soils from Rothamsted and Woburn Farms that had been under either arable crops that had received fertilisers or manure or were permanent grass or woodland for more than a century. Other soils had been in arable rotations, under leys, or fallowed for shorter periods.

At Rothamsted, mainly on the Batcombe series, soil mechanical composition varied little and the measurements were related more to large differences in soil organic matter than to soil texture. At Woburn, less retention of soil organic matter related to larger instability and erodability of the soils on the Cottenham and Stackyard series, particularly under arable conditions, contrasted with the more stable behaviour of those on the Evesham series.

Acknowledgements

The author thanks E. Bird for soil mechanical analyses, F. V. Widdowson for help in sampling the Reference Experiment soils, R. H. Turner for the 'Stereoscan' photographs and D. J. L. Robinson for chemical analyses and density measurements.

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APPENDIX TABLE 1

Composition and treatment of Rothamsted soils

Site	Sampled	Treatment	Soil composition (%) Coarse sand 2000–200 μm	Fine sand 200–20 μm	Silt 20–2 μm	Clay < 2 μm	Free $CaCO_3$	Organic carbon*	Total nitrogen
Broadbalk (Section I)									
Plot 2	1977	> 100 years arable, wheat since 1843 + 35 t ha^{-1} FYM annually	6	45	22	20	1·8	1·91	0·25
Plot 3	1977	> 100 years arable, wheat since 1843, no fertilisers or FYM	5	45	25	20	2·4	0·53	0·10
Plot 5	1977	> 100 years arable, wheat since 1843 + annual fertilisers (PK Mg)	6	45	25	20	1·9	0·58	0·10
Plot 7	1977	> 100 years arable, wheat since 1843 + annual fertilisers (N2 PK Mg)	4	45	22	25	0·3	0·72	0·10
Plot 11	1977	> 100 years arable, wheat since 1843 + annual fertilisers (N2 P)	6	42	23	25	0·6	0·75	0·11
Plot 12	1977	> 100 years arable, wheat since 1843 + annual fertilisers (N2 P Na)	6	43	22	24	1·4	0·82	0·11
Broadbalk Wilderness									
Wooded section	1977	> 100 years arable, self-sown woodland since 1886	5	40	20	25	0·6	3·45	0·40
Grazed section	1977	> 100 years arable, self-sown woodland (1886–95), stubbed (1895–1957), grazed since	5	38	20	26	0·2	3·42	0·46
Stubbed section	1977	> 100 years arable, self-sown woodland (1886–95), stubbed since	6	40	19	26	0·2	2·78	0·34
Geescroft Wilderness	1961	> 100 years arable, self-sown woodland since 1883	5	44	25	21	0·0	1·50	0·17
Knott Wood	1961	> 200 years woodland	3	35	21	24	9·0	2·63	0·31
Manor Wood	1961	> 100 years woodland	15	35	23	22	0·0	2·21	0·20
Highfield Pasture	1977	> 200 years grass	4	38	22	23	0·0	3·34	0·45
Highfield Fallow	1977	> 200 years grass, cultivated bare fallow since 1960	4	42	28	22	0·0	1·17	0·17
Fosters Old Fallow	1977	> 100 years arable, cultivated bare fallow since 1960	7	40	26	24	0·2	0·78	0·14
Fosters New Fallow	1977	100 years arable, cultivated bare fallow since 1975	7	44	24	21	0·4	0·78	0·12
Great Field IV									
Permanent grass	1977	> 100 years grass	11	40	22	20	0·0	2·41	0·27
Reference Expt. (a)	1977	> 100 years grass, arable + fertilisers since 1956	9	42	19	27	0·1†	1·67†	0·24†
(b)	1977	> 100 years grass, arable + FYM since 1956					0·1†	2·14†	0·28†

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APPENDIX TABLE 1—*continued*

Composition and treatment of Rothamsted soils

Site	Sampled	Treatment	Soil composition (%) Coarse sand 2000–200 μm	Fine sand 200–20 μm	Silt 20–2 μm	Clay <2 μm	Free $CaCO_3$	Organic carbon*	Total nitrogen
Manor Walled Garden	1961	Heavily manured during last century	16	30	19	20	2·6	3·67	0·42
Barnfield									
Plot 10	1960	$>$100 years arable, root crops + 35 t ha^{-1} FYM annually	8	34	20	31	0·4	1·87	0·27
Headland	1960	$>$100 years cultivated and mainly uncropped	8	39	23	29	1·1	0·50	0·09
Mean			7·0	40·3	21·3	23·6	1·1	1·84	0·23
Range			3–16	30–45	19–28	20–31	0–9·0	0·50–3·67	0·09–0·46

* Walkley–Black uncorrected values
† Mean values for four blocks. Mechanical analyses on oven-dried basis

APPENDIX TABLE 2

Composition and treatment of Woburn soils

Site	Sampled	Treatment	Soil Composition (%) Coarse sand 2000–200 μm	Fine sand 200–20 μm	Silt 20–2 μm	Clay <2 μm	Free $CaCO_3$	Organic carbon*	Total nitrogen
Stackyard Field									
Section I	1960	$>$100 years arable	43	35	8	10	0·0	0·64	0·10
Series B	1977	$>$100 years arable, cultivated bare fallow since 1960	44	32	9	13	0·0	0·41	0·06
Series C (a)	1973	$>$100 years arable, grass since 1960	56	24	6	11	0·3†	0·94†	0·13†
(b)	1973	$>$100 years arable, arable since 1960	50	30	7	11	0·2†	0·78†	0·11†
Butt Furlong	1960	Permanent grass	60	21	5	8	0·0	1·41	0·15
Butt Close	1962	Ploughed after 7-year ley	70	14	5	7	0·0	1·15	0·14
Pightle	1977	$>$100 years grass	57	18	6	9	0·0	2·61	0·31
Broad Mead Field	1961	Permanent grass before 1958, arable since	15	12	16	41	0·2	3·40	0·28
Honey-Pot Field	1961	Permanent grass	18	13	15	36	0·2	4·48	0·56
All soils Mean			45·9	22·1	8·6	16·2	0·1	1·76	0·20
Range			15–60	12–35	5–15	7–41	0–0·3	0·41–4·48	0·06–0·56

* Walkley–Black uncorrected values
† Mean values. Mechanical analyses on oven-dried basis