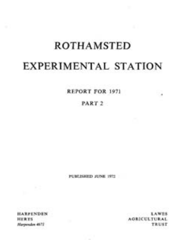
Rothamsted Experimental Station Report for 1971 Part 2


ROTHAMSTED
EXPERIMENTAL STATION
REPORT FOR 1971
PART 2

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Problems With Cultivations and Soil Structure at Saxmundham

G. W. Cooke and R. J. B. Williams

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Problems with Cultivations and Soil Structure at Saxmundham

G. W. COOKE and R. J. B. WILLIAMS

In previous accounts of work at Saxmundham we have mentioned that difficulty in obtaining good and deep tilths for arable crops may be a reason for some of the poor yields recorded (Williams & Cooke, 1971). We now describe experience in working the land and record properties of the soil that make it 'difficult'; we also give results of experiments testing soil conditioners and in Part 2 discuss recent ideas on the nature of soil structure and their application to Saxmundham soil.

Part 1. Experimental work and observations

The problems we have met are not new and Oldershaw (1941) discussed them when describing the first 40 years' results of Rotation I and Rotation II experiments. Unseasonable rainfall always lessened yields. Neither surface nor subsoil drain well and Oldershaw wrote 'In spite of the fact that the district is one of the driest in England, this heavy land is frequently in so wet a state that neither horses nor men can walk on it. . . . The Saxmundham land is very similar to an enormous area of boulder clay which occurs in various parts of England. Much of this has in the past been allowed to go derelict, has become covered with thorn bushes and is now being reclaimed at enormous cost. All this has happened during the past 20 years with land immediately adjoining the experimental fields at Saxmundham. It is hardly necessary to point out that efficient drainage on this type of land is essential. The tractor, by rendering rapid cultivation possible when weather conditions are favourable, greatly helps in tillage operations and in the difficult task of keeping the land reasonably free from weeds.'

Problems associated with arable farming on soils with unstable structure were discussed in the Agricultural Advisory Council's (1970) inquiry. Diminishing organic matter in unstable soils was considered a cause for concern when these soils were used for arable farming. Problems of damaged structure caused by heavy machinery used on wet soil were accentuated by bad drainage, weeds, pests and diseases. Among the soils of the Eastern Region that are considered 'potentially susceptible' (i.e. to structural damage) and need skill in managing them in wet and adverse seasons were 'The sandy clay loams and silty clay loams of the boulder clay areas of Suffolk, Norfolk and the northern parts of Huntingdonshire particularly when they are non-calcareous. These soil types are abnormally unstable to water and mechanical force and over-compact easily at any depth within the top 15 in. In many areas poor natural drainage contributes to these problems.' Saxmundham soil is in this category, being a badly drained sandy clay. The Report gives general advice on the need to improve drainage, comments on the value of 'periodic grass breaks', and states that farmers need to be better informed about their land and how to manage it. No cure is suggested for the basic problem that certain soils are unstable in water and may drain badly, and will be compacted by heavy machines, except to advise more research. The merits of leys are stressed in the Report and it may be that in parts of the country where we now grow little but cereals, a period under grass will check soil-borne pests and diseases and add enough root residues to benefit later crops. (Our experiments on herbage crops at Saxmundham are reported on pp. 95–121).

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The difficulties we have met

Seedbeds. There is only a small range in moisture content of Saxmundham soil between the stages when it is too wet to work without damage, and too dry for aggregates to be broken by cultivating. Mole draining in 1964 and deeper ploughing to about 10 in. since 1965 have improved drainage and aided penetration of rain. But these changes, especially deeper ploughing, have introduced other problems. Often good seedbeds for winter wheat could not be made because the deep furrow slices could not be broken to small clods and crumbs, especially when the autumn was dry. The soil does not weather readily to give good *deep* structure, even during cold winters; spring seedbeds have been unsatisfactory, with fine crumbs overlying massive clods remaining from ploughing the previous autumn. A rough surface aids superficial drainage in wet years but cloddy sub-structure must interfere with supplies of nutrients and water to roots and may be responsible for our failure to get *consistently* good yields of arable crops.

Crop yields. Wheat has been the most disappointing crop at Saxmundham and we have not averaged much more than half the 3 tons/acre of wheat regularly produced in the Ley–Arable experiments at Rothamsted. By contrast, grass leys treated with N yield at least as well at Saxmundham as at Rothamsted; lucerne at Saxmundham has yielded more and persisted better than at Rothamsted and much better than at Woburn, where it is usually damaged by nematodes. Yields of cereals at Saxmundham have varied much more than we expect in the Rothamsted Ley–Arable experiments. Table 1 shows yields with NPK fertilisers and with FYM in Rotation I experiment in 1966–69.

TABLE 1

Yields in Rotation I experiment at Saxmundham, 1966–69

	Wheat yields (cwt/acre)		Barley yields (cwt/acre)		Sugar beet (tons/acre of roots)	
	NPK fertilisers*	FYM†	NPK fertilisers*	FYM†	NPK fertilisers*	FYM†
1966	32·2	18·7	29·1	34·2	10·1	13·5
1967	35·3	45·3	24·9	24·0	16·3	19·2
1968	42·7	48·4	37·5	34·3	16·8	19·7
1969	30·8	28·6	29·6	23·2	18·5	11·6
Mean	35·2	35·2	30·3	28·9	15·4	16·0

* Fertiliser dressings were (per acre) 112 lb N, 39 lb P and 93 lb K; some of the crops had extra top-dressings of 56 lb N/acre in 1967–69.

† FYM dressing was 12 tons/acre from 1966; in addition these plots had 56 lb N/acre in 1967–69.

Weather and crops. Some poor yields can be explained, others not.

Wheat yields in 1966 were small because it was attacked by Wheat Bulb fly, which was favoured by a preceding fallow. They were best in 1968, which is only explained if the weather sequence of near average rainfall from October 1967 to February 1968, followed by a dry March, April and May, and then a wet June and July, suits the crop at Saxmundham. Wheat yields in 1971 were slightly larger than in 1968 and, at 53 cwt/acre, were the best we have taken at Saxmundham. Fig. 2a of our other paper (p. 112) shows that these two years had very similar small moisture deficits from March to the end of July and that moisture relationships were very different from those of the dry years (1967 and 1970) and the wet year (1969). Certainly the 5½ in. of rain in September 1968 set the scene for 1969's very poor yields by making ploughing difficult, good cultivations impossible and the seedbed very poor. Large clods weighing 1 cwt or more, formed when

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ploughing for wheat in autumn 1968, were covered by a little tilth, but were ploughed up unchanged a year later. Plate 1 shows a *small* clod (12 kg) ploughed up in 1969; it was formed at least a year earlier.

Barley yields were small in 1967 because the soil was damaged when removing the previous sugar beet and by ploughing in October and November 1966, which provided 4·3 and 3·4 in. of rain respectively. The 1967 barley seedbed had to be prepared above waterlogged clods that dried but did not weather during spring and summer; undoubtedly the dry June and July of 1967 made it impossible for barley to secure enough water. Barley in 1969 also suffered from the unsatisfactory ploughing in 1968.

Sugar-beet yields seem to depend on the amount of leaching of nitrate that occurred during the springs of 1966, 1967 and 1969 (Williams, 1971a). After realising in 1966 that much N may be lost, in 1967, 1968 and 1969 we tested top-dressings (applied early in summer). The beet responded well to extra N in 1967 and 1969 when there was much leaching in spring, but not in 1968. Yields for these years in Table 1 were from 100 units N/acre in the seedbed plus a summer dressing of 50 units N/acre.

Some 'best' yields at Rothamsted, Saxmundham and Woburn were compared in Part 2 of last year's Report (pp. 92–94). In 1966, 1967 and 1969 Saxmundham wheat yielded similarly to the national average, barley yields fluctuated and were roughly average in 1966 and 1969 but much poorer in 1967. Surprisingly, both wheat and barley yielded best in 1968—when both national average yields, and yields at Rothamsted, were much less than usual. We suggest that this was because the wet June and July, which decreased yields elsewhere, suited Saxmundham cereals by providing enough water for crops rooting in cloddy seedbeds. (This happened again in 1971 when we harvested 53 cwt/acre of wheat.)

Causes of poor yields. To yield well, crops need *from soil*, adequate nutrients and water and conditions that allow healthy roots to grow. Small yields of wheat and barley at Saxmundham cannot be made large simply by giving more nitrogen fertiliser, although the soils have enough of other nutrients, as they have received large fresh dressings of P and K fertilisers and already had good reserves. Reporting on the 'Intensive Wheat' experiment Slope and Broom (1971) said—'known foot and root-rot diseases seem not responsible for the small yields. There has been much less take-all and eyespot in this than in comparable experiments at Rothamsted and Woburn. This may explain why previous cropping has affected grain yields so little at Saxmundham but certainly not why the best yields have been so much less than those at Rothamsted.' Crops have been regularly examined and leaf diseases are usually no more prevalent than at Rothamsted, nematodes less prevalent. Hence, if pathogens are responsible, these have yet to be identified.

Our explanations of poor cereal yields at Saxmundham are: (i) the soil may not supply enough water; (ii) physical conditions hinder root growth and so restrict uptakes of water and nutrients.

Comparisons of Rothamsted, Woburn and Saxmundham soils

Rothamsted soils are mostly clay loams and silt loams lying above well-drained subsoils resting on chalk. They are stable when wetted, are easier to cultivate than most clays and suit continuous arable cropping. Broadbalk field has grown wheat continuously since about 1840 and Lawes (1895) considered the field had been arable for several

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centuries before. Best yields on Broadbalk are about 50 cwt/acre—nearly 1 ton/acre more than the national average yield; other fields on Rothamsted farm give more wheat—as much as recorded in Britain.

The most important property of a soil for successful arable cropping may be one that is typical of Rothamsted soils; any clods formed by ploughing, cultivating or traffic, break up as they dry and after rewetting a rough tilth forms naturally. This does not happen at Saxmundham. 'Weather' gives only a surface tilth, clods formed by ploughing often persist unchanged a year or more and cultivators and harrows do not produce a deep tilth. Plate 2 compares two small clods, both picked from furrows of autumn-ploughed land and kept in the laboratory. The clod from our worst soil at Rothamsted—Barnfield headland—cracked as it dried and shattered under its own weight to form a mass of angular aggregates. Saxmundham soil, taken from the 'best' area of the field, shrank but did not crack and the clod retained its massive structure when dry.

The dry Saxmundham clods have a 'close' surface free from cracks and large pores. Rain passing through a 'seedbed' containing such clods is shed by them; the clods do not absorb water readily and most of the soil they contain is 'out of circulation', is not penetrated by roots and does not contribute water or nutrients to the crop. The clods do not absorb enough water for frost to break them in winter. For example, clods sampled in autumn had only 13–14% moisture; they were deep frozen for seven days but when thawed they regained their original appearance and did not crack or disintegrate. Plate 3 shows differences in reaction to wetting and weathering. Two portions of the clods shown in Plate 2 were wetted by filling the trough with water. The Rothamsted clod wetted quickly and in a few seconds exploded to form a mass of small aggregates that were quite stable. The Saxmundham clod wetted much more slowly, only its surface weathered during the first few minutes and a core of unshattered soil remain an hour later. The fine soil falling from the Saxmundham clod was not aggregated, but consisted of coarse sand particles with the spaces between filled with very fine material—the beginning of another massive and structureless clod.

Woburn soil is typically a sandy loam overlying well-drained sand. As most soils that contain much sand and little clay, its aggregates are not stable in water, crumbs fall to their constituent particles when wetted; the particles resort and pack more closely so that pore space and water-holding capacity are lost and drainage through the surface deteriorates. Ploughing, which is always easy, usually restores damaged Woburn soil to a crumbly free-draining condition. The 'Classical' experiment on Stackyard field at Woburn grew cereals continuously from 1879 to 1951; the soils have only about 1% of organic matter but the only physical problems in managing them for arable crops are that pans are easily formed by ploughing, by rotary cultivators and by the wheels of heavy machines. When the soil becomes waterlogged, it slakes to form 'single grain' structure and then is easily eroded and gulleys 6 in. deep have been formed by large rainfall. Nematodes infest many crops severely at Woburn (no attack has been observed at Saxmundham). Nematodes are most active in well-drained soils at field moisture capacity, conditions Woburn provides in wet seasons.

Physical properties compared. Table 2 gives some measurements of physical soil properties. Saxmundham soils were from plots of Rotation I experiment that had (i) no manure or fertiliser since 1898 or (ii) 6 tons/acre of FYM each year; the subsoil from the FYM-treated plot was also examined. Rothamsted samples included very old permanent grass on Highfield and two soils from Barnfield (considered the most difficult to cultivate of Rothamsted fields). The Barnfield headland has been continuously cultivated, while growing poor unmanured crops, often no crop at all, for more than a century; the other

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TABLE 2

Properties of Saxmundham, Rothamsted and Woburn soils

Annual treatment	Saxmundham RI experiment			Woburn	Rothamsted		
		FYM		Stackyard field	Highfield	Barnfield headland	Barnfield
	No manure	Surface soil	Subsoil	Fallowed	Permanent grass	No manure	FYM
Absolute density (g/ml)	2·52	2·49	2·54	2·61	2·46	2·57	2·48
Bulk density <2 mm soil (g/ml)	1·39	1·34	1·39	1·34	1·16	1·48	1·37
Water holding capacity <2 mm soil (%)	44	51	51	27	68	46	62
pH (1 : 2·5 water suspension)	8·2	8·0	8·4	5·5	5·6	8·3	7·8
Mechanical analysis							
Stones (>6 mm) (%)	9·0	3·0	4·8	0·1	3·9	21·6	9·6
Gravel (2–6 mm) (%)	2·7	3·9	6·1	0·9	2·2	2·2	3·4
Coarse sand (2–0·2 mm) (%)	30·8	38·2	34·8	43·3	5·5	8·1	7·9
Fine sand (0·2–0·02 mm) (%)	27·4	21·4	17·0	31·6	40·2	37·7	33·2
Silt (0·02–0·002 mm) (%)	8·8	9·1	8·3	9·2	22·2	22·0	19·3
Clay (<0·002 mm) (%)	22·9	19·9	30·4	12·9	23·5	28·6	29·5
Coarse particles (6–0·02 mm) (%)	60·9	63·5	57·9	75·8	47·9	48·0	44·5
Water slaking instability (%)	25	19	21	40	−0·3	15	0
Dry mechanical slaking (%)	19	17	18	26	15	15	23
Total mechanical slaking (%)	61	71	62	65	42	58	57
Breaking strength (kg)	11·6	6·1	17·0	4·9	3·5	10·7	9·8
Organic carbon* (%)	0·94	1·56	0·32	0·67	2·36	0·50	1·87
Total N (%)	0·13	0·19	0·06	0·09	0·29	0·09	0·27
Density of soil after compaction† (g/ml)	1·52	1·61	1·52	1·55	1·04	1·54	1·33

* Walkley and Black method, uncorrected values.
† Force used to compact was 7·0 kg/cm^2.

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Barnfield soil has had 14 tons FYM/acre annually. The Woburn soil is from an area of Stackyard field which has been arable for roughly a century and is now fallowed.

Absolute density varied slightly according to amounts of organic matter in the soils; Rothamsted and Saxmundham soils were similar, Woburn soil was a little more dense because it contains much coarse sand.

Bulk densities were measured on aggregates prepared in the laboratory by freezing and thawing, then drying and collecting the soil passing a 2 mm sieve. The only large differences were that soil under old pasture on Highfield was less dense and Barnfield headland soil more dense.

Mechanical analyses. Saxmundham soils contained much coarse sand, Rothamsted little. Table 3 shows more detailed mechanical analyses, published by Hodge (1972) for Saxmundham and by Avery and Bullock (1969) for one profile on Broadbalk field at Rothamsted. Most of the 'coarse' sand at Saxmundham is in small particles (500 μ–200 μ). Rothamsted soils have little coarse sand but nearly half of Woburn soil is in this fraction. All Rothamsted soils have much 'fine' sand (Table 2), but Table 3 shows that, in one Broadbalk soil, its size is near to the silt fraction, 31% of the soil being 20–50 μ. Saxmundham fine sand is coarser than Rothamsted fine sand. Rothamsted soils have twice as much silt, but about as much clay as Saxmundham soils.

TABLE 3

Comparisons of mechanical analyses of Broadbalk and Saxmundham soils

Broadbalk Profile 3 (Avery & Bullock 1969)		The 'slope' at Saxmundham 0–18 cm (Hodge 1972)		
Fraction (μ)	% of soil	Fraction (μ)	% of soil	
200–2000	5·7	2000–1000	0·9	26·0
		1000–500	2·5	
		500–200	22·6	
100–200	9·5	200–100	18·7	
50–100	4·9	100–75	3·4	
20–50	31·0	75–20	11·5	
2–20	24·3	20–2	11·4	
<2	24·7	<2	28·8	

Table 2 shows results of the physical tests proposed by Williams and Cooke (1961) and used by Williams (1971b). They were made on aggregates of laboratory-prepared soil.

Instability in water is measured by the loss in pore space when small aggregates of soils prepared in the laboratory are immersed in water and slake. Crumbs of Saxmundham soil were much less stable than those of other soils we have examined with similar clay contents. Annual dressings of FYM have not made it stable. (This instability of *small* crumbs that wet easily should not be confused with the *stability* of large clods shown in Plates 2 and 3—which is because they do not have cracks and pores through which water can enter.) The soils of Barnfield headland, after growing poor crops or none for a century, slaked less than Saxmundham FYM-treated soil; regular dressings of FYM have made Barnfield soil quite stable.

Dry mechanical slaking measures loss in pore space when aggregates are compressed, as in cultivating dry soil. Saxmundham soil was compressed a little more than Barnfield

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headland; giving FYM had no effect on the strength of Saxmundham soil, but weakened the Barnfield aggregates. Highfield soil, rich in the organic residues from old grass, was not easily compressed. Woburn soil lost much pore space.

Total mechanical slaking measures loss in pore space when wet soil is compressed, as in ploughing or cultivating. Saxmundham soil was compressed more than the Barnfield soils. FYM made Saxmundham soil compress more easily, but had no effect on Barnfield soil. The densities of the soils were measured after compressing (by a force of 7·0 kg/cm²) when wet; the density of compressed Saxmundham soil increased where FYM had been given, whereas Barnfield soil given FYM was much less dense than the headland soil.

Field measurements of bulk density at Saxmundham. Bulk densities in Table 2 were measured on aggregates prepared in the laboratory. Table 4 gives densities of cores of soil (1 in. deep) taken from the field during autumn by the method described by Zwolinski and Rowe (1966).

TABLE 4

Bulk densities of Saxmundham soils

	Bulk density, g/ml	
Subsoils from site of RI experiments (28–30 cm deep)		
Texture: Gleyed clay	1·60	Mean 1·71
Texture: Sandy loam	1·76	
Texture: Clay	1·77	
Headland used for traffic to experiments	1·65	
Surface soils (0–15 cm) from barley stubble of RI experiment		
Annual treatment: No manuring	1·62	Mean 1·63
Annual treatment: NPK fertilisers	1·67	
Annual treatment: FYM	1·60	
Sites of experiments on herbage crops		
After three years of lucerne	1·47	
After two years of clover and one year of spring wheat	1·51	
Arable sites without traffic		
Site of soil structure experiment	1·28 (mean of 8 plots)	
Experiment on gypsum (untreated plots)	1·34	
Experiment on soil settling	1·37	
New clover–grass leys, three years old (mean of two sites)	1·32	
Headland permanently under grass (no traffic)	1·13	

Subsoils from many plots of Rotation I experiment varied greatly in texture over quite small distances, as described by Hodge (1972), all had large densities. Surface soils taken from cereal stubbles also became dense from settling and spring cultivations. Obvious ruts and tracks left by tractors and combine-harvesters were avoided in sampling, but an uncropped headland used by vehicles was not more dense than the soil of cereal stubbles. Land where lucerne had grown for three years, and the adjacent site where two years of clover had been followed (without ploughing) by spring wheat, had become quite dense although a tractor had not been used on the area after sowing.

Several sites used for microplot experiments, and for observations on soil properties, were worked by hand from the sides of the plots and not compressed at all. These assumed densities of 1·28–1·37—similar to that of soil under three-year-old clover–grass leys. There are no plots of permanent grass at Saxmundham but a permanently-grassed headland that carries no traffic had bulk density resembling that of soil under old grass at Rothamsted.

Salter and Williams (1969) compared apparent specific gravities of Saxmundham, Rothamsted and Woburn soils. Their soils, taken by the method described by Salter

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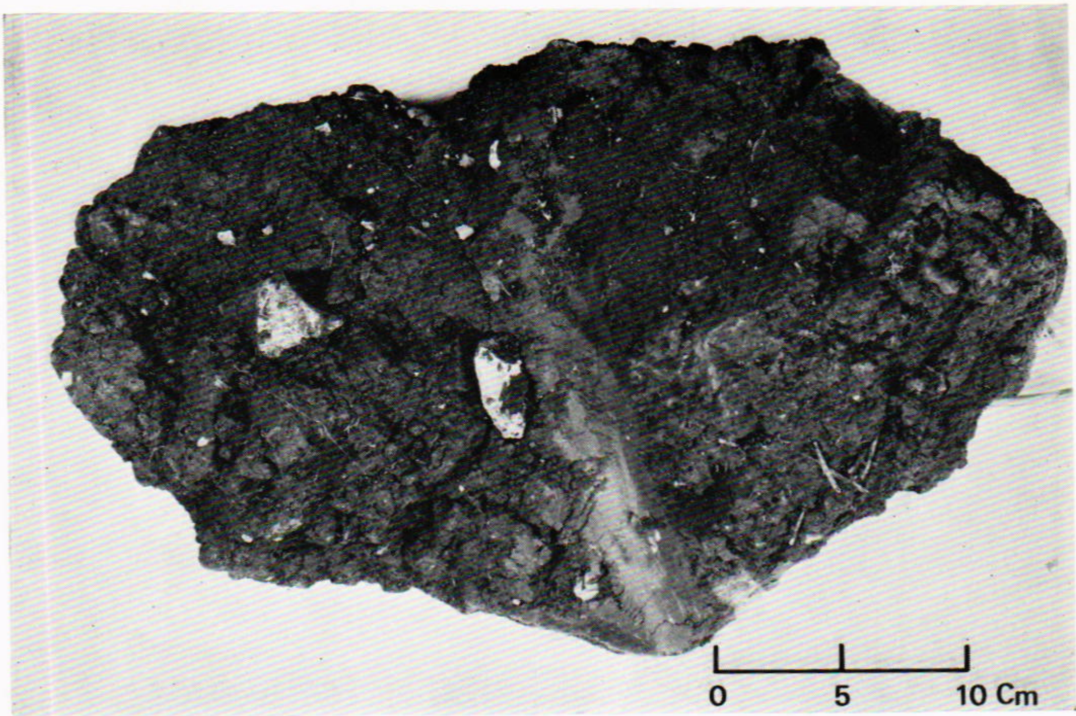


Plate 1. Clod of Saxmundham soil, formed by ploughing in autumn 1968 and ploughed up again unchanged in autumn 1969.

Photo: Rothamsted Experimental Station

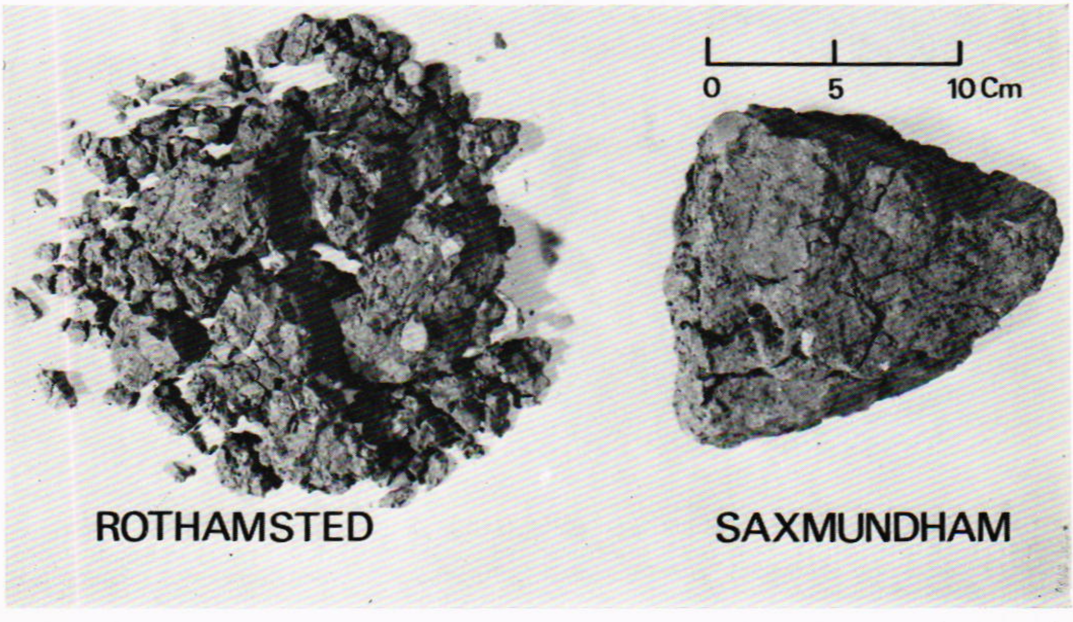


Plate 2. Small clods of surface soil from Barnfield Headland (Rothamsted) and from *Harwood's Field* (Saxmundham) taken from plough furrows in autumn 1969 and allowed to dry indoors.

Photo: Rothamsted Experimental Station

[*facing p.* 128]

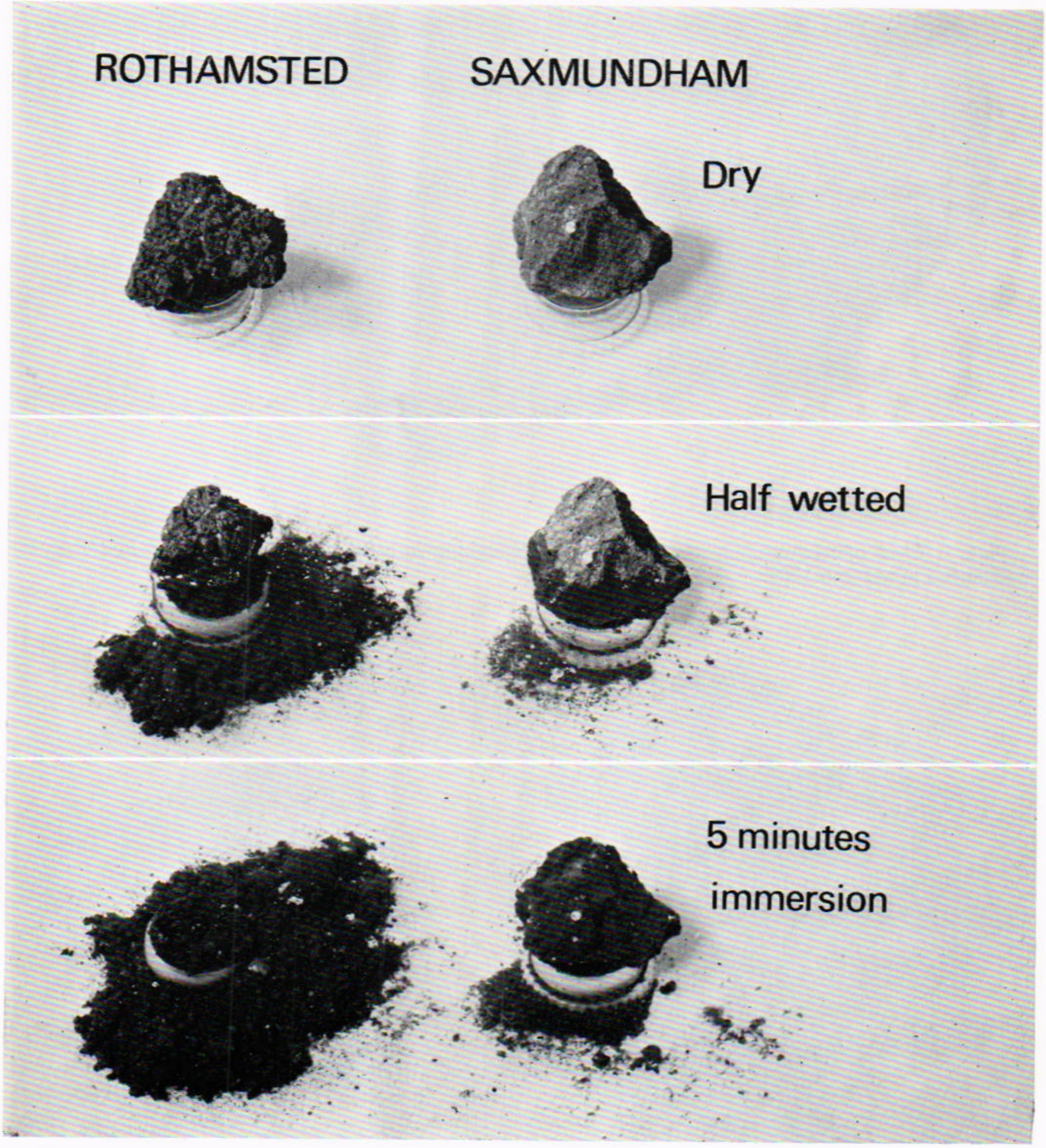


Plate 3. Differences in speed of weathering of Barnfield (Rothamsted) and Saxmundham soils. Portions of the clods shown in Plate 2 were placed in a trough and flooded from below. Upper photograph shows air-dry clods, centre photograph shows the clods half-wetted (that from Rothamsted disintegrated instantaneously); the lower photograph shows the clods after being completely immersed for about five minutes.

Photo: Rothamsted Experimental Station

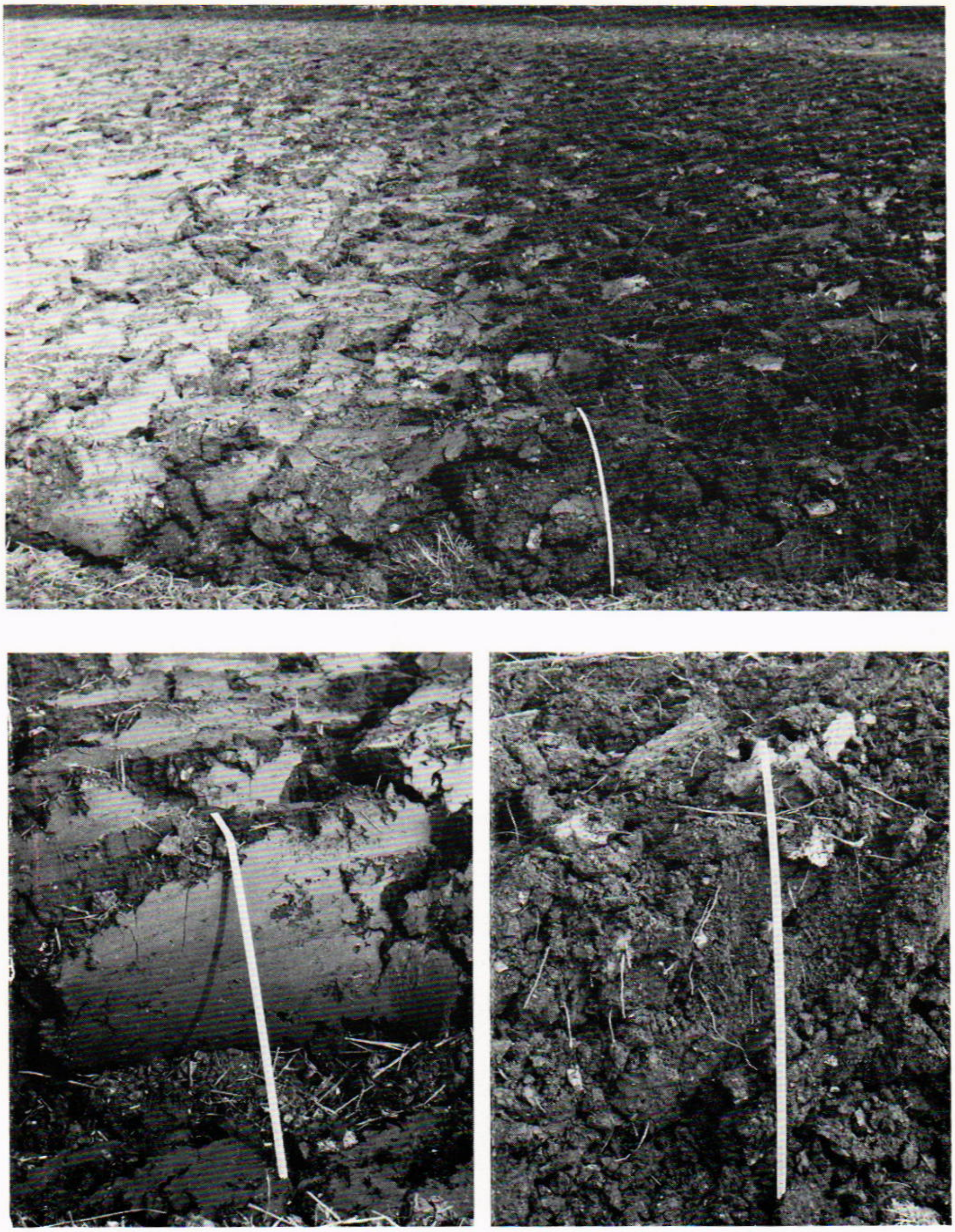
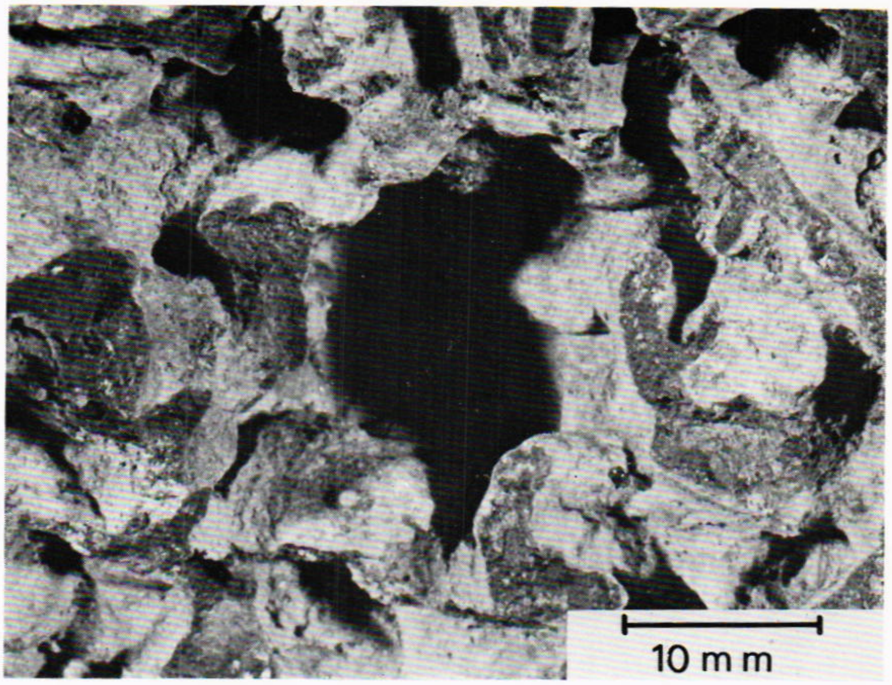


Plate 4. Saxmundham soil ploughed in September 1969. *Left*—after wheat. *Right*—after lucerne and clover. Detailed photographs show the massive clods forming the plough furrows of land where wheat had grown and the shattered open structure of land ploughed after lucerne.

Photos: G. W. Cooke



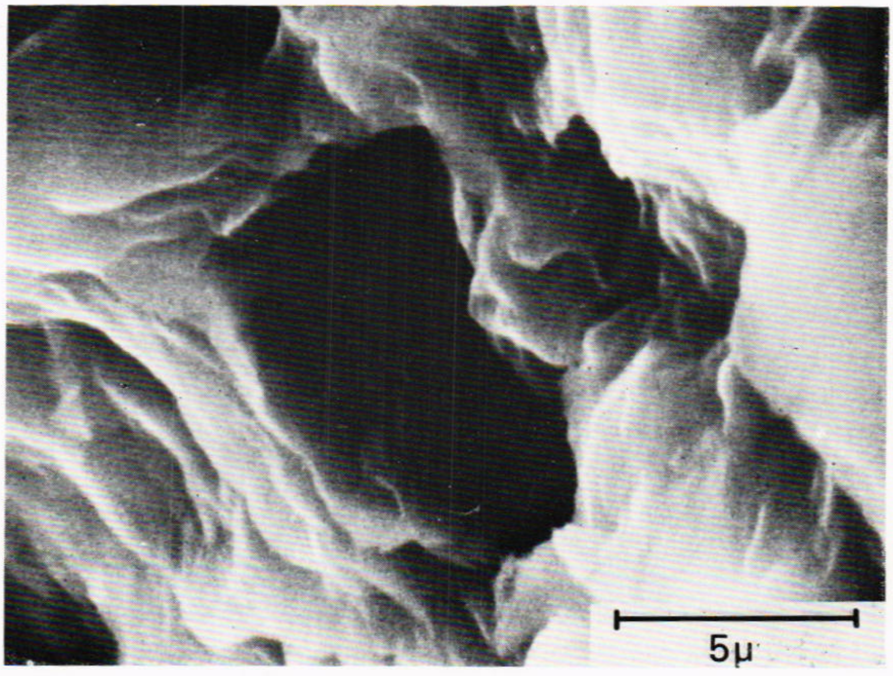


Plate 5. Comparisons of large and small 'pores' in structures cemented by ferric compounds. *Top*—a piece of porous tropical laterite; the pore in the centre is 10 mm in diameter. *Bottom*—'Stereoscan' photograph of red Rothamsted subsoil show pores of about 5 μ diameter.

Photo: Rothamsted Experimental Station

(1967) during May 1967 before the open structures of the seedbeds had been completely destroyed by summer rain and harvest traffic, gave these results:

Site and crop	Without FYM, g/ml	With FYM, g/ml
Barnfield (spring beans)	1·24	1·18
Broadbalk (winter wheat)	1·30	1·30
Lansome field, Woburn (carrots)	1·59	1·28
Saxmundham (spring barley)	1·43	1·28
	After cereals	After ley
Stackyard field (Woburn)	1·65	1·31
Park Grass (Rothamsted)	1·22	

Woburn soil settled sooner than the clay soils, FYM prevented this consolidation, as did a period under a ley. Saxmundham soil without FYM had become more dense than soils from Barnfield or Broadbalk at Rothamsted. FYM diminished the consolidation of Saxmundham soil, but had little effect at Rothamsted.

Pore space. Core samples of subsoil from RI experiment had a mean bulk density of 1·71. As the absolute density of this soil was 2·55, total pore space was 33%. Many gravimetric determinations of soil moisture made between 1967 and 1969 gave these results:

Depth, in.	Soil moisture (% w/w) Range	Mean	
0–9	11·5–19·2	16·4	
18–24	14·8–20·5	17·7	17·4
30–36	14·7–20·9	17·0	

As 17·4% w/w is equivalent to 29·8% v/v with a density of 1·71, on average, the subsoil had only 3% of air-filled space during most of the year, and must often be anaerobic during wet weather. Roots of perennial crops (such as lucerne) penetrate the subsoil but few roots of annual crops do so. Lucerne roots penetrated deeply during the three years the crop lasted, perhaps by following cracks and removing enough water to keep surrounding subsoil aerobic.

Moisture-holding capacity. Bad soil structure interferes with the steady supply of water to a growing crop. Although such effects are easy to postulate, they are difficult to measure. Water-holding capacities of the soils were compared by Salter and Williams (1969). Moisture characteristics were measured on samples taken from the surface 6 in., deeper samples were taken to 12 in. at Woburn and Rothamsted but not at Saxmundham because at 9 in. the soil changed abruptly to compacted clay. The 'available water capacity' (AWC) of Saxmundham soil was comparable to those of Woburn and Rothamsted soils in the surface 9 in., but the heavy clay below this depth would probably restrict rooting and the moisture characteristics of the layer was not studied. The *effective* capacity of Saxmundham soil to hold water for crops must be less than the capacities of Rothamsted and Woburn soils, because the sudden change to a less pervious medium checks roots and water movement. Also, the massive clods in tilled top-soil did not contain available water because they were not readily moistened by rain and lacked pores. Their behaviour in absorbing and supplying moisture was nearer to that of gravel. At Rothamsted and Woburn there is no sharp transition in texture and structure on passing into unploughed soil. If Saxmundham top-soil is limited to a 9 in. layer, whereas

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the surface 12 in. behaves as top-soil in supplying water to crops at Rothamsted and Woburn, available water capacities of top-soil become:

	Inches of water	
	Without FYM	With FYM
Barnfield	1·73	1·91
Woburn (Lansome field)	1·59	1·95
Saxmundham	1·35	1·38

Table 5 gives measurements made on soils treated in comparable ways, with and without annual dressings of FYM. Park Grass soil held most water, 2·8 in. per ft. FYM (14 tons/acre) given each year greatly increased the available water capacities of Rothamsted and Woburn soils but the 6 tons/acre given annually at Saxmundham did not. Land recently ploughed from a ley on Stackyard field at Woburn held 25% more water than land in continuous arable.

TABLE 5

Available water capacities (AWC) of surface 6 in. of Rothamsted, Woburn and Saxmundham soils

	AWC inches/6 in. of soil	
	Without FYM	With FYM
Barnfield } Rothamsted	0·72	0·82
Broadbalk } Rothamsted	0·82	1·07
Lansome, Woburn	0·77	0·92
Saxmundham	0·90	0·92
	After ley	No ley
Stackyard, Woburn	1·04	0·83
	Permanent grass	
Park Grass, Rothamsted	1·41	

Saxmundham soil differed from the others in two ways: (1) the shallow sandy clay top-soil is sharply separated from the clay subsoil so that the whole profile probably contains less useful water than profiles at Rothamsted and Woburn; (2) available water capacity at Saxmundham was not increased by applying FYM every year.

Effect of organic matter on water-holding capacity. Organic matter in soils is commonly supposed to improve the supply of moisture to crops, increasing both the total quantity and the amount 'available' (i.e. retained at small tensions). Table 6 (Salter & Williams, 1969) shows much of the extra available water held by Rothamsted and Woburn soils treated annually with FYM, or had grown grass, was retained at small matrix suctions and therefore could be readily extracted by roots. The increases in the moisture retained were most at smallest suctions but persisted through the range used. FYM caused a much smaller increase in moisture retained at smallest suction at Saxmundham than elsewhere and there was no effect at all at the largest suction. A relevant contrast is between Barnfield soil where FYM increased the percentage of water held at 0·05 atm by 4% and at 15 atm by 2%; corresponding increases for Saxmundham soil were only 1·5% and 0·1%.

Drainage at Saxmundham

Most of the Rothamsted and Woburn farms have not been artificially drained, but Saxmundham field is tile-drained by a system described by Williams (1971a). One criticism

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TABLE 6

Percentages of soil moisture (w/w) retained at increasing suctions by surface soils from Rothamsted, Woburn and Saxmundham

	Total FYM applied tons/acre	Carbon in air-dry soil %	Suction (atm) 0·05	0·33	1·0	2·0	15
			% of soil moisture retained (w/w)				
Barnfield, Rothamsted							
− FYM	—	0·9	21·6	16·7	15·6	14·9	11·9
+ FYM	1736	2·6	25·5	21·1	19·3	18·1	14·0
Park Grass, Rothamsted	—	2·7	33·0	26·4	23·0	20·4	13·8
Lansome, Woburn							
− FYM	—	0·9	12·2	10·6	8·8	7·8	4·2
+ FYM	750	2·3	20·1	15·7	13·2	11·9	8·1
Stackyard, Woburn							
Cereals	—	0·8	13·9	12·1	10·5	9·4	5·5
After ley	—	1·9	20·1	15·9	13·1	11·5	6·8
Saxmundham							
− FYM	—	1·3	22·7	19·3	18·2	16·8	12·2
+ FYM	414	2·0	24·3	20·3	19·9	17·2	12·3

(from Salter & Williams (1969))

of modern farming methods is that cultivations used in continuous arable farming compress subsoils and interfere with drainage. To test this criticism we compared the records of drainage left by Oldershaw (1935–38) with our recent observations. (Unfortunately the plan of the drains on Harwood's field before 1948 is not known (as records were lost in a fire).) Table 7 shows that in 1968–71 the drains ran on several times as many days in the year as they did in 1935–38. The two wet years 1935 and 1936 had almost the same rain as 1968 and 1969; the drains ran in 1935–36 on 39 days, in 1968–69 on 272 days. Very much better drainage in the 1960s is no doubt partly because new drains were put in by the National Agricultural Advisory Service in 1948; but deeper ploughing each year since 1964 and mole-draining in 1964 have probably contributed more. Until the 1950s the land was ploughed and cultivated by horses; a light tractor was used from 1949 but harvesting was by binder. We have used a heavier tractor and a single furrow deep plough to turn the soil 10–12 in. deep since 1964. This has stopped the surface run-off and erosion that commonly occurred with shallower ploughing until 1964. Modern methods of cultivating, a heavier tractor, and using a heavy combine harvester have not damaged drainage.

TABLE 7

Comparisons of drainage flows at Saxmundham in 1935–38 and 1968–71

	Total annual rainfall (in.)	No. of days drains were running*
1935	27·5	13
1936	27·6	26
1937	29·0	32
1938	19·6	11
1968	27·1	110
1969	27·6	162
1970	22·8	95
1971	25·0	80

* We have no definition of 'running' in 1935–38 but it is likely that very small flows were ignored. We have also ignored all days with total flow less than 2·5 litres/minute from the four drain outfalls we observe.

That soil conditions are better now than in the 1930s when the land was worked by horses is confirmed by examining Oldershaw's (1935–38) records. For example—'There

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was very little frost during winter and the spring of 1937 must be . . . one of the worst seasons on record for getting crops drilled.' (Nearly 13 in. of rain had fallen by the end of April.) 'The horse hoeing of corn crop was in many cases impossible.' (The corn harvest was secured in good condition, but) . . . 'owing to adverse weather earlier in the year the yield of corn and roots was very much below the average and it is one of the worst seasons on record.' The best yields from Rotation I experiment were on the NPK-treated plots and were: 14·5 cwt/acre of wheat, 11 cwt/acre of barley and 13·5 tons/acre of mangolds. Trist (1947) stated that 1947 was the worst year for wheat since 1899. The crop on all plots without P fertiliser failed completely—which had never happened before. A very wet autumn delayed work in 1946 and wheat was sown late. Weeks of frost, snow and rain followed; afterwards the summer was hot and dry. Yields per acre from NPK-treated plots were 6·5 cwt of wheat, 16 cwt of barley and 6·8 tons of mangolds; FYM-treated plots yielded no more wheat, less barley and half as much mangolds.

Other dry summers have favoured wheat at Saxmundham: Oldershaw (1938) wrote 'The abnormally dry spring and summer (of 1938) resulted in very good yields of corn. The old adage "drought never brought dearth to England" still holds good when applied to corn. Root crops were severely checked.' Yields per acre from NPK-treated plots were 33 cwt of wheat, 16 cwt of barley and 6·6 tons of mangolds. By contrast, the best yields recorded in the modified Rotation I experiment were in the wet season of 1968 (Fig. 2a, p. 112) when rain in June, July and August was about an inch more than average; they were 48 cwt of wheat, 43 cwt of barley, 20 tons of sugar beet and 30 cwt of beans. Although we are not satisfied with the yields at Saxmundham, comparisons with the past suggest that modern farming has improved the way the soil can be worked and greatly increased yields.

Experiments made to improve Saxmundham soil

Field experiments have tested alternative ways of preparing seedbeds, the effects of gypsum (often suggested for improving clay soils) on soil porosity, and the effects of soil conditioners on yields.

Seedbed cultivations. Draycott *et al.* (1970) compared methods of preparing seedbeds considered good and bad for sugar beet in three experiments, and got the expected result—untimely cultivations, which compacted the seedbeds, usually decreased seedling populations and always decreased yields of roots and sugar.

The value of gypsum. Gypsum is used to assist leaching of sodium from saline soils. Calcium sulphate has been suggested for improving the structure of non-saline soils by varying exchangeable cations and electrolytes in the soil solution and so altering the forces between soil particles that arise from electrical interactions between their charges (Greenland, 1971). Whether gypsum made Saxmundham soil more porous was tested on an area of Grove Plot that had been dug to produce a coarse tilth. Coarse (10–16 mm) and fine (<3 mm) particles of gypsum were applied in April 1968 at 10 tons/acre on the surface of some plots and dug in on others. The site was not cultivated or compressed and weeds were killed by fine sprays of herbicides. Cores from the surface inch had the bulk densities, shown at top of page 133, one year after applying gypsum.

Gypsum diminished bulk density. Penetrometer readings (shown above) made on 22 July 1969 showed that all gypsum treatments diminished the surface strength of the soil. (For comparison, soil on an adjacent barley experiment had a surface strength of 5·4 kg/cm^2.) We do not know whether the open structure could persist in soil that carried usual traffic.

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	Penetrometer readings kg/cm²	Bulk density (g/ml)	
		Mean	Range of values
Average effects			
Gypsum	0·88	1·14	0·91–1·25
None	1·90	1·34	1·27–1·41
Coarse gypsum			
On surface	0·96	1·19	—
Dug in	1·43	1·12	—
Fine gypsum			
On surface	0·54	1·11	—
Dug in	0·60	1·15	—

Soil conditioners. A microplot experiment started in spring 1966 tested the following large amounts (totalling 10% of the volume of soil) of several 'conditioners' dug in 9 in. deep by hand: Granulated peat (17 tons/acre); FYM (34 tons/acre); coarse and fine 'Lytag' (approximately 40 tons/acre); two plastic wastes (approximately 0·5 tons/acre)—polystyrene (shredded) and polyurethane (chopped). All these (except polyurethane) were applied at 5% (v/v) in April 1966 and again in April 1967; the whole of the 10% (v/v) dressing of polyurethane was given in 1967. 'Krilium' soil conditioner was tested as a surface dressing of 10 cwt/acre in the spring of each year.

Peat and FYM were chosen because they are traditional soil improvers. 'Lytag' is a sintered product made from 'fly ash' from power station furnaces; the granules have large pore spaces and we hoped they would increase pore space and water-holding capacity of the soil. The inert plastic materials were used to see whether they would check the natural compacting of the soil. 'Krilium' is a chemical conditioner that stabilises a prepared structure.

The soil was not cropped in 1966 but pore space, measured in autumn, was increased 4–5% by polystyrene, peat and fly ash, and 2·4% by 'Krilium'. All materials increased the water held by the soil (measured by nylon/stainless steel resistance units):

	Mean moisture content during the year (% w/w)
Untreated	19
'Lytag'	21
Peat	23
Polystyrene	23
FYM	25
'Krilium'	25

'Krilium' preserved the surface tilth made by cultivating during spring; the other materials did not, and the surface soil slaked as severely on treated as on untreated plots. These benefits of annual dressings of 'Krilium' in stabilising a surface tilth prepared by hand tools persisted until the experiment stopped in 1971; the other conditioners had no effect.

The value of these changes in physical properties was tested by growing lettuce in 1968. The crop was planted as uniform-sized seedlings in holes (filled with fine soil) made in the undisturbed settled 'seedbed'; all plots were given adequate NPKMg fertilisers. Table 8 shows that all the conditioners diminished yield of tops and roots of lettuce by amounts that were two or more times the standard error and the loss in yield on 'Krilium'-treated plots was significant. These remarkable results suggest that there is no simple way of making Saxmundham soil less 'difficult' by increasing the pore space of the top-soil or by stabilising its structure.

Sugar beet was grown on the experiment by P. C. Longden of Broom's Barn. The first crop was sown on 8 April 1969 when the seedbed was warm and moist but fine and workable. None of the treatments altered seedling emergence or weight of seedlings harvested

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TABLE 8

Yields of lettuce grown in 1968 in an experiment testing soil conditioners at Saxmundham

Soil conditioner	Yields of dry matter (cwt/acre) Tops	Roots
None	14·2	0·7
FYM	12·3	0·4
Granulated peat	12·4	0·5
Coarse 'Lytag'	11·1	0·5
Fine 'Lytag'	11·1	0·5
Polystyrene	12·0	0·5
Polyurethane	12·6	0·6
'Krilium'	9·6	0·4
Standard error	±1·08	±0·07

on 13 May. A second sowing was made on 23 May when the seedbed was wet and sticky. Only 55% of seedlings emerged on peat-treated plots; 72% emerged on all other plots except with 'Krilium', where slightly fewer emerged. Yields at harvest on 8 October were not affected by conditioners, though these made the roots more fangy. Sugar beet was sown again in 1970 but the soil conditioners did not affect emergence of the seedlings.

Changes in soil structure caused by herbage crops

The sites of the Intensive Wheat Experiment described by Slope and Broom (1971) and the clover, lucerne and grass experiments described elsewhere in this Report (pp. 95–121) were observed during and after ploughing in 1969; cereals were grown in 1970 and 1971, their yields are given in pp. 116–117.

Field observations, 1969–70

After wheat in 1969 the soil ploughed up in compact and massive lumps with smeared bases and sides.

After beans in 1969 that followed wheat in 1968, the soil crumbled and was free from massive clods.

After red clover in 1967–68 and spring wheat in 1969 the soil ploughed easily and gave structure similar to that after beans.

After lucerne in 1967–69 ploughed soil formed crumbled plough furrows without clods. Thick lucerne roots broken off in ploughing were 16 in. long and 0·1 in. thick at the break, and were not constricted at plough depth. This land that had carried lucerne could have been sown at any time after ploughing and without cultivating. By contrast, the soil of plots in wheat in 1969 baked hard during October and the clods could not be broken. A surface tilth was forced early in November, but underneath was little but massive clods and large voids (and these clods were turned up again when ploughing the following autumn). Plate 4 shows these contrasts between land ploughed after lucerne and after wheat.

After timothy-meadow fescue ley was grown for three years the site was ploughed early in November; the furrows appeared similar to those of adjacent land that had been in

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barley. During the following spring the surface of the land after grass drained better, dried sooner and was ready for sowing sooner than land in barley the previous year.

The arable land of Rotation I cultivated on 30 April 1970, had an excellent *surface* tilth, formed by frost from the ploughed land. This tilth was 1–2 in. deep, but below it the cultivated layer was composed only of hard but wet clods. The soil ploughed from three years of grass was soft; the grass roots had made it possible for frost and alternate wetting and drying to weather the soil deeply, and it was free from clods such as formed the lower layers of the seedbed on adjacent land ploughed from barley stubble.

Bulk density and pore space. The sites of the herbage-crop experiments were sampled one inch deep just before ploughing in autumn 1969; bulk densities were measured and roots extracted from the samples were weighed:

	Bulk density (BD), g/ml	Total pore space, %	Oven-dried roots, % (w/w)
After lucerne 1967–69	1·48	42	0·38
After clover 1967–68 and wheat 1969	1·51	41	0·36
After grass 1967–69	1·56	39	1·00

Samples from individual plots showed that soil after lucerne was least dense (BD = 1·44) where the crop had grown best with the large dressing of phosphate and potassium fertiliser. This was also true for the clover–wheat site; well-fertilised soil had BD = 1·48 and contained most roots. Least bulk density of soil under grass (1·51) was where much N had been given and the crop had been cut often. Bulk densities were largest (1·61 and 1·62 respectively) where N had not been applied and where the largest dressings given to infrequently cut crops had thinned the plants and left much bare soil. Although the average bulk density was least after lucerne, this soil contained less than half as much roots in the surface as soil after grass.

The grass roots extracted from the cores were very contaminated with soil and were not analysed. Lucerne roots contained (in dry matter) 1·78% N, 0·23% P and 0·84% K and 24·8% of total soluble carbohydrates (the carbohydrates present may promote bacterial growth and the production of polysaccharides that stabilise structure (see p. 137)).

Yields of following cereals. Yields of cereals grown after legumes and after grass are given elsewhere in this Report (pp. 116). Unfortunately the very dry summer of 1970 limited yields of all crops at Saxmundham. Cappelle winter wheat yielded 40·6 cwt/acre after lucerne and 36·5 cwt after clover and spring wheat. In the adjacent Intensive Wheat experiment the largest yield was 30·8 cwt/acre; the extra 10 cwt/acre after lucerne may reflect the improved soil structure, but this is uncertain. In 1971 wheat was grown again and the best yield was 53 cwt/acre—the largest we have recorded from any treatment at Saxmundham but no more than was grown by a second wheat crop in the adjacent Intensive Wheat experiment. Barley grown in 1970 after grass yielded 33·5 cwt/acre from the best treatment; a little more than the same variety gave in a nearby experiment on Grove Plot but much less than was grown in Rotation I experiment on land arable for 70 years. In 1971 Midas barley grown on the site of the grass experiment gave very poor yields because of a severe attack of brown rust; the best was 21·5 cwt/acre, no more than on nearby land that had not grown grass and only half as much as Julia barley (which was little infected by rust) yielded on Rotation II experiment.

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Conclusions

The experiment testing soil conditioners showed that treatments that lessen bulk density and increase pore space in surface soil do not necessarily increase crop yields and may diminish them. Stabilising the aggregates of a carefully-prepared seedbed by using 'Krilium' did not improve germination of sugar beet seed or increase the yield of lettuce or sugar beet, although the crumb structure was completely preserved; crops on untreated plots, where the surface soil slaked, yielded more. Treatment with gypsum lessened the bulk density of the soil, but its effect on crops was not tested.

Visible improvements in soil structure were caused by growing lucerne, red clover, beans or a grass ley. Evidence of the worth of these changes is not conclusive as replicated experiments could not be made, but the cereal yields suggest that: (1) growing lucerne improved the soil for the following wheat crop but that the effects did not last for two years; (2) three years of grass did not improve yields of following barley.

Our measurements and observations suggest that several properties of Saxmundham soil combine to make it difficult to work and lead to smaller and more variable yields than at Rothamsted: (1) bad drainage; (2) instability of soil *crumbs* when wetted; (leading to) (3) large bulk density (and therefore small pore space); (4) the inability of sub-surface clods to 'weather', so that the lower horizons of seedbeds are cloddy, and massive structures formed by cultivation persist for a season or more. *Small* aggregates are undoubtedly unstable because of the mechanical and mineralogical composition of the soil; the bad drainage may be from the same cause and because of the way the soil was deposited as a boulder clay. Large clods are compact and do not weather because they shrink as they dry and do not have cracks or pores large enough to allow water to enter quickly by capillarity. The pressure of air trapped in capillary spaces of large Rothamsted clods is, no doubt, the reason for their shattering quickly when wetted. The stable units of Rothamsted soil are the small aggregates (up to say 2–4 mm in diameter); Saxmundham aggregates of this size are not stable, and the stable units are either the ultimate fine particles of the soil or the massive large clods made by cultivations.

Part 2. Modern views on soil structure, their implications for Saxmundham soil

Definitions of good and bad structure are conventional. It is *assumed* that soil should be stable and should contain an assembly of pores and solid particles of definite sizes; 'maintaining' structure means preserving these arrangements, improving structure means that sizes of particles and pores are altered towards proportions considered more satisfactory. There is little *proof* that 'improving' structure will increase yields, or that the conventional definitions of good structure are relevant to crop growth. Some definitions are based more on aesthetics than agricultural concepts; stable crumbs look 'nice' or are pleasant to walk on. Concepts of the gardener's 'ideal' soil, dark coloured, rich in organic matter and crumbly, are often transferred to agriculture. But many peat soils, mostly organic matter and all crumbs, do not produce large yields of some agricultural crops. Neither are the 'black earth' czernozem soils notably more productive than other soils with less pleasing appearance. An increase or decrease in organic matter may be a symptom rather than a cause of changing fertility. Percentage of organic matter *inevitably* diminishes when land that has been 'rested' under grass or woodland is used for crops needing annual cultivation. But when organic matter starts to diminish after a period during which it was constant, the soil is probably being over cultivated, and the remedy is less cultivation. This may need a better balance between 'resting' crops (those not involving ploughing or cultivating) and annual cultivated crops; applying FYM is not necessarily a remedy.

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Criteria of good structure. Modern ideas on soil structure were fully discussed by Greenland (1971) and Russell (1971). Greenland lists changes that improve structure as:

(a) *Increases in* (1) porosity; (2) aggregate and micro-aggregate stability; (3) water retention at any given suction and in available water.
(b) *Decrease in* bulk cohesive strength.

Soil aggregates consist of small groups, or domains, of oriented clay particles, themselves associated in micro-aggregates, which are bonded together in some way to form larger aggregates. Greenland gives the upper size limits as: domain 5 μ, micro-aggregates 1000 μ; aggregates 5000 μ (5 mm), aggregates larger than 5 mm are 'clods'. Best physical conditions for growth are when aggregates are 1–5 mm diameter; these allow air and water to move, yet retain adequate water. The forces *between* aggregates should be weak (as in Rothamsted soil) so that seedlings and roots are not hindered; forces *within* aggregates, and *between* micro-aggregates, should be large enough to prevent aggregates being destroyed by rain or cultivating (again Rothamsted soil has this property). Forces that hold particles together depend on: (i) exchangeable cations; (ii) electrolyte concentration; (iii) the dielectric constant of liquid surrounding the particles; (iv) materials absorbed on particle surfaces that change electrical and hydration properties; (v) on substances that form interparticle bonds (e.g. chemical conditioners). Greenland thinks that improving soil structure involves both producing and stabilising aggregates of 1–5 mm diameters; also that physical processes alone are not enough to produce stable aggregates, but earth-worms and other soil animals are essential for reworking the soil 'to reassemble domains into micro-aggregates and arranging these in aggregates more porous than those previously existing'. Earth-worms and other soil animals are rarely seen at Saxmundham. We have no information on numbers and species, and this is a gap in our information about the soil.

Processes that stabilise soil structure. The distribution of added organic matter is more important than its amount or composition; improvements in structure seem primarily from polysaccharides adsorbed on walls of the coarse (2–50 μ) pores between domains and micro-aggregates. When polysaccharides are absorbed by adjacent particles forming the walls of pores, the aggregate is held together by strong interparticle bonds. Organic compounds that accumulate in soil under pasture include polysaccharides with large molecular weights produced by bacteria small enough to live in pores of 2 to 50 μ sizes. Greenland concludes 'the distribution of fine root material as substrate, and production of active polysaccharides by bacteria in pores . . . is the basis of soil structure improvement by pastures'.

Aggregates can also be stabilised by inorganic cements, especially substances that dissolve during some soil conditions and are reprecipitated when conditions alter. Calcium carbonate, aluminium and iron hydroxides and silica all act in this way. Greenland considers that, in most surface soils, iron and aluminium hydroxides are secondary in maintaining structure to organic compounds, but probably they interact with organic materials. In subsoils, iron and aluminium oxides undoubtedly influence stability of aggregates independently of their interaction with organic materials. The importance of ferric oxide in giving stable structure to North American soils was also discussed by Kemper and Koch (1966). Plate 5 shows an interesting similarity between the porous structure of a tropical laterite, in which particles are cemented together by ferric oxides and hydroxides, and the micro-porosity of a crumb of the red Rothamsted subsoil in which ferric compounds may also act as cements. The pores in the laterite were about 5000 μ in diameter, those in the crumb of subsoil (photographed by 'Stereoscan' electron microscope) about 5 μ.

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Some of the concepts found useful by civil engineers in classifying subsoils may help in understanding what makes some clay soils unstable in water. For example, Smalley (1971) discussed the nature of the bonds between the particles of soils that are unusually unstable. Long-range bonds between clay particles depend on charges on the particles, on electrolytes in soil water, and the polarised nature of water. Short-range bonds between uncharged particles depend on *contact* between particles. Some subsoils called 'quick-clays' are very unstable when disturbed (and become a hazard because land-slides develop); they are dominated by short range bonds developed between particles of near-clay size but free from charged clay minerals. Smalley shows how cohesion in such soils depends on particle size. When particles are mainly of sand size, their weight prevents interparticle bonding, but when silt and clay sizes predominate the particles cohere. We do not know whether Saxmundham soil contains fine material that is in uncharged particles. If it does, this might be a reason for massive clods forming and persisting when the soil dries, and the cause of the soil being unstable when wetted.

Soil conditioners. When 'Krilium' and other chemical conditioners were introduced 20 years ago, they made it possible to test theories that stabilising structure improved crop growth. Obstacles to developing such materials are that the criteria that define a soil in 'good condition' are often unknown, so the purpose of the conditioner is uncertain. A chemical conditioner of the 'Krilium' type, or a rubber latex emulsion (Williams, 1965), does not promote good structure in a soil already bad; it can only stabilise structure obtained previously by cultivating or by frost. Conditioners may be useful where structure deteriorates rapidly—as on soils that 'cap' after heavy rain, or become impervious when watered in a glasshouse; but used on a slaked or cloddy soil they will simply stabilise the soil in that bad physical state. Bulky conditioners such as plastic wastes have their effect by propping soil aggregates apart. Large amounts must be used, otherwise an unstable soil can envelop the particles of conditioner. Plastic wastes are often very stable in soils and, if non-porous, hinder root penetration, in contrast to organic manure, which decomposes to leave spaces into which roots grow and which are enriched by nutrients mineralised from the manure.

Reports of experiments from many countries show that chemical conditioners succeed in stabilising the crumbs of most kinds of soil, and that the effects often last for more than a year. Many of the experiments show improved emergence and early growth of the crops. On some soils crop yields have increased proportionately with improvements in structure as characterised by aggregation, aeration, porosity and permeability; in other soils, the conditioners have not affected yields. Usually where soil conditioners have increased yields, it has been of quickly-growing crops with a small root range. Benefits to common farm crops have been measured less often. For example, of 24 experiments done in 1952–53, in Canada, with oats, sugar beet, wheat, maize, barley and potatoes, although the conditioners consistently improved the physical characteristics of the soils, yields were increased significantly in only two.

Avoiding difficulties in managing Saxmundham soil

There is no immediate prospect of *curing* the difficulties in making crops yield well at Saxmundham. They arise from the composition of the surface soil and the way it has been formed from the variable but usually compacted and ill-drained boulder clay underneath. Compaction may be lessened and drainage improved by skilful choice of crop and timely cultivations. Problems will have to be avoided, because their basic solution is impossible (if soil composition is at fault) or distant (if better knowledge of how to

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produce desirable structure is to come from future research, but as Ede (1971) pointed out, it usually takes many years before basic research on soils benefits farmers).

The conditions we consider responsible for difficulties with Saxmundham soil are defined earlier (p. 136) and discussed in this last section.

Drainage and cultivations. Hodge (1972) and others have stressed the badly-drained subsoil and the few roots it contains. Deeper ploughing improved water acceptance and made the surface soil dry sooner in spring because there is now a large volume of disturbed soil to hold rain. However, this change has removed difficulties caused by wet weather from the surface, but has not solved them. When much rain falls water accumulates on the plough sole because it enters the cultivated layer quicker than it can leave. Now that surface drainage has been improved, shallow rooting crops are much more susceptible to the effects of summer drought.

Difficulties in subsoil drainage are inherent in Saxmundham profiles. By contrast Rothamsted soil is a model of a well-drained heavy soil. The relatively good drainage encourages deep rooting, so promoting intensive and persistent fissuring in the finer-textured subsoil. These conditions suit wheat because its deep roots use subsoil moisture (and take up nitrate leached down the profile). The average Saxmundham seedbed for winter wheat, a tilth with massive and long-lasting clods beneath, can hold little water; the sharp change to compacted slow draining subsoil may prevent wheat making enough deep roots to obtain water and nitrate during dry periods.

Possibly iron hydroxide cements contribute much to the stability of the red Rothamsted subsoils, which have a coarse fissured structure permitting rapid drainage to the chalk below. Wherever continued arable cultivation has been successful at Rothamsted for a century or more, the subsoils are well drained and have a deep reddish-brown colour. Most Saxmundham subsoils show by mottling that drainage is poor, and many samples examined have no brown or red colours to indicate that ferric hydroxides are present, and plant roots are scanty or absent. The compact poorly-structured subsoils may be perpetuated by reducing conditions that destroy ferric hydroxide cements between particles.

Both *cultivations* and *deep-rooting crops* grown for more than one year can improve drainage. Subsoiling helps to break pans and re-establish drainage cracks, but its success depends much on when the work is done (Hull & Webb, 1967); even under favourable conditions subsoiling only improves a small part of the whole volume of soil. Rotations of herbage crops and cereals should be devised to avoid traffic during wet weather. Chisel ploughing may often be better than normal ploughing for autumn-sown wheat; spring work on fine or wet soil should be minimised. Some work may be done before seedbeds are prepared (e.g. spreading P and K fertilisers); N-fertilisers may be applied after sowing when the soil surface is dry (this may also make the fertiliser more efficient by avoiding leaching by spring rainfall). Land should be ploughed deeply during dry autumns, but not in wet. Late ploughing when the soil is frozen could be better than when it is wet. Spraying against weeds, pests and diseases may be combined with applying N fertilisers as liquids. 'One-pass' systems of preparing a seedbed and sowing in one operation may have special advantages on these soils.

If root crops have to be grown, 'bed' systems may have advantages where the area growing the crop is never compressed by implements, wheels being confined to a narrow track. This was the basis of the stetch system of farming formerly used in East Suffolk; the land was laid up in drill-widths with water furrows between in which the wheels ran. The Saxmundham plots were cropped in this way until the 1950s. Deeper ploughing has made water furrows unnecessary, but the areas compressed by tractor wheels need to be limited. We have found serious damage caused to seedbeds made in the following

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spring after sugar beet has been harvested during a wet autumn. Much barley yield was lost in this way in 1967. When sugar beet is grown on land of this kind, it *must* be harvested early in autumn before the soil has become saturated. The economics of sugar-beet growing on 'difficult' soils must take account of the effect of growing the beet on yields of following crops.

In some years good *surface* tilths are obtained by a little cultivation of weathered soil, in others more force has to be used to break clods. However a tilth of crumbs (5 mm or less in diameter) is obtained, it seems that it soon slakes and slumps to masses of large bulk density (1·6 or more).

Diminishing organic matter is often suggested as the cause of poor soil structure. Saxmundham soil shows that a large content of organic matter does not, *per se*, suffice to give good structure. Saxmundham soil is richer in organic matter than many Rothamsted soils that are much more stable; 6 tons/acre of FYM given each year for 70 years has not made a stable structure. Greenland (1971) stressed the *form* of organic matter as more important than its amount. The great improvement in structure caused by lucerne (Plate 4) cannot be related to fine roots left in the soil—for there were little. The deep tap-roots no doubt improved drainage and aeration by the holes they left and by drying the subsoil. The lucerne roots contained 25% of 'total soluble carbohydrates', and this fraction may be very significant if the carbohydrates from decaying roots are assimilated by bacteria in pores while they produce polysaccharides that form strong and lasting interparticle bonds.

Formation of aggregates and clods. The nature of the bonds between particles may affect slaking in water and modify the formation of massive structures. Instability in water increases as the proportion of particles coarser than 200 μ increases (Williams, 1971b); Saxmundham soils have 40% or more in this size range and we assume that the soil is unstable because the coarse sand prevents sufficient bonding between clay particles. Possibly Rothamsted and Saxmundham soils differ in the kinds of clay minerals that affect structure. Whatever the reasons, Rothamsted soils seem to have micro-aggregates (defined by Greenland) that are very stable and do not slake, whereas the aggregates of Saxmundham soil fall to constituent particles on slaking. At the other extreme of aggregate size, the large clods of Saxmundham soil do not disintegrate on drying as Rothamsted clods do (Plate 2). Saxmundham clods appear to shrink on drying, and shrinkage may make them impervious to rain when 'perched' above the plough sole in a seedbed, so that the slaking is prevented.

Some conclusions

Soils that are 'difficult' when used continuously for arable crops do not have stable micro-aggregates as the basic unit of structure. In soils that are easy to cultivate, these micro-aggregates provide a foundation that: (a) contains residual pore space to resist extreme compression; (b) serves to initiate the natural 'weathering' processes that 're-structure' compressed soil by increasing pore space and lessening clod size. Usually the 'difficult' heavy soils have impeded drainage; anaerobic compacted subsoils may be a major cause of the bad physical properties that make such land difficult to work, poor structure in subsoils being perpetuated by waterlogging. Mechanical composition must be important too. Saxmundham soil contains 30–40% coarse sand, 20–30% fine sand, and little silt. The 'easy' Rothamsted soils have little coarse sand but 50–60% of fine sand plus silt; clay contents are similar.

The power and implements used in modern farming can destroy the arrangements of aggregates and pores that we think favour plant growth. Scientific work has shown how

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soil may be managed to avoid damage, and how it may be improved by the roots of some crops, but it has not shown how to bring clods to crumbs. Bad drainage can and should be improved, but other difficulties must be avoided because they cannot be cured. All agree that tractors and other machines should not be used on wet land, but, in a wet year, this is a counsel of perfection to a sugar-beet grower. It may be worth losing the larger profit from a cash root crop such as sugar beet because of the hazard to soil entailed by late harvesting.

We think the land is best used for rotations of cereals and leys. Herbage crops will improve soil structure after a period of cereals and will help to control weeds that are not easily controlled in continuous cereal cropping. Because we have not proved that the better soil structure found after ploughing leys increases yields of cereals, the herbage crops grown must themselves be profitable. In cultivating for cereals, compressing the soil should be avoided by making most appropriate use of: (i) deep ploughing and subsoiling (needed to avoid surface flooding and to help water penetrate); (ii) shallow ploughing (to avoid deep layers of unweathered clods under autumn seedbeds); (iii) surface cultivations that do not invert the soil. The experiments needed to guide farmers in their choice of alternative cultivations *must* be made on the soils where the problems exist. Better methods for difficult soils cannot be devised by interpolating or extrapolating from the results of experiments on easier land.

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