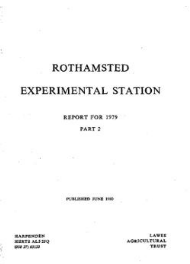
Rothamsted Experimental Station Report for 1979 Part 2



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The Soils of Woburn Experimental Farm
III. Stackyard

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D. W. KING, D. G. M. HALL and C. P. MURPHY

Abstract

The soils of Stackyard Field are divided into four series (the Cottenham, Stackyard, Flitwick and Husborne), all of which have previously been reported elsewhere on the farm. The distribution of series and within-series variations of topsoil and subsurface texture and stone content are all expressed in detailed maps.

Micromorphological features and physical properties of the Cottenham, Stackyard and Flitwick series are described in relation to selected profiles. Thin sections provide evidence of clay translocation and of considerable heterogeneity within all horizons above approximately 1 m depth, which results mainly from soil faunal activity. The size distribution of finer drainable pores is described for a profile of Stackyard series. Measurements of bulk density and water retention at various matric potentials reveal large differences between the series in air capacity, available water and non-available water, the Cottenham series being considerably more droughty than the Flitwick; in all three of these components of the total pore space, the Stackyard occupies an intermediate position between the other two series.

A correlation between available water and silt content for the samples on which physical measurements were made is used to construct a map of the distribution of profile available water to 80 cm depth over the field. The effect of changes in available water on potato yields is demonstrated by reference to results of the Six-course Rotation experiment (1930–60). For many years there are modest correlations between available water and yield irrespective of treatment. However, in years with moderate or high summer rainfall there was a strong depression of yield on plots with the most water-retentive soils. This effect is attributed to pests or disease. Penman's limiting potential deficit probably varies with soil type, and revised values for three crops grown on the Cottenham, Stackyard and Flitwick series are calculated from the ratios of their available water contents.

Introduction

Stackyard, a field of 10·55 ha area, lying approximately 2 km south-west of Crawleymill Farm, was acquired in 1876 as the main experimental field at Woburn, because few of the others provided large enough areas of sandy soil. We have studied the soils of this important experimental field in detail, because variations in crop yields in some past experiments were not clearly related to treatment or weather, and inherent soil fertility differences across the field have often been postulated to account for this. However, the nature of such differences has never been investigated, and much of the information contained in experimental results has consequently been ignored. Also, 'uniform soil' is often given as a prerequisite for experiments, though it is less often stated in which properties the uniformity is desired. Stackyard has a fairly uniform topsoil, and at first sight seems to offer the desired uniformity of growing medium, but subsurface variability suggests this may not be true. We therefore measured the variability of some soil factors that are

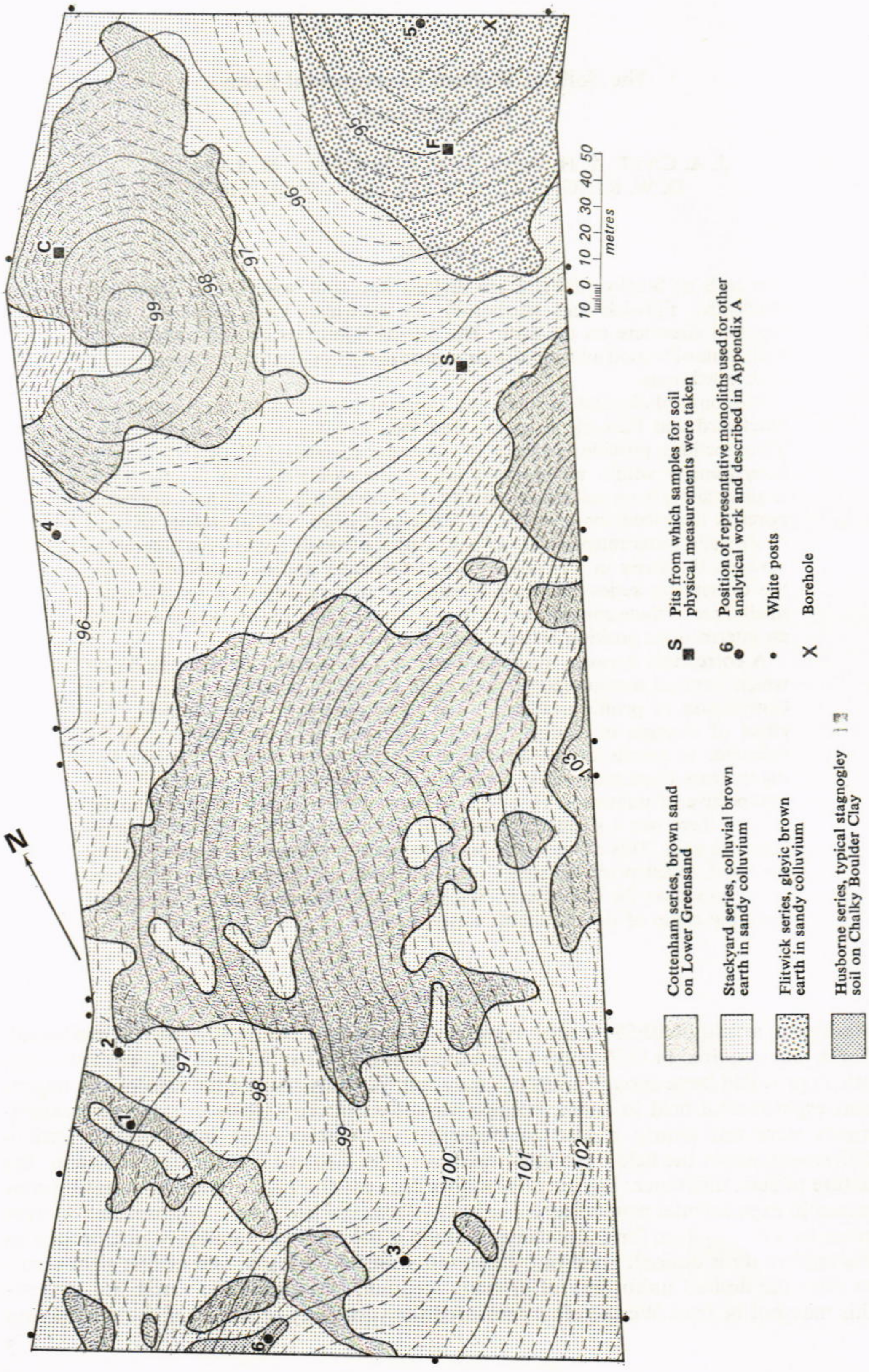

FIG. 1. Map of Stackyard Field, Woburn Experimental Station, showing distribution of soil series, topographic contours at 0·2 m intervals OD, and location of Proline cores 1–6, soil pits C, S and F, and borehole X.

likely to influence crop growth, and present these so that they can be considered in the design of future experiments.

Stackyard is bounded to the east by the Woburn–Husborne Crawley road (A 418), which skirts Woburn Park, and to the west by meadows bordering the canalised Crawley Brook, so that for the most part the field slopes gently to the west. However, the surface contours (Fig. 1), interpolated from heights measured on a 10 m rectangular grid over the field, show that the uniform westward slope is modified across the southern part of the field by a shallow east–west valley, and that in the north-west a small isolated knoll is separated from the remainder of the field by a shallow saddle between NE–SW and SSW–NNE trending valleys. The overall height range is 8·8 m, the highest point (>103·0 m OD) being adjacent to the road about half way along the eastern side of the field, and the lowest (<94·4 m OD) near the north-east corner.

Geology

The whole field is underlain by Lower Greensand (Woburn Sands), probably of considerable thickness. It has never been proved beyond 6·7 m depth anywhere on the field, but nearby boreholes at Birchmoor Farm (0·5 km to the west) and Birchmoor Pumping Station (1 km north-west) proved >59 m and >71 m respectively of sand and sandstone (Woodward & Thompson, 1909, 66; Horton *et al.*, 1974, 35). Quaternary deposits (Chalky Boulder Clay, glacial gravel and colluvium) are widespread on the field, but are thin (<2 m) and are best discussed in relation to the soils.

Distribution of soil types

Four soil types occur on Stackyard, namely the Cottenham, Stackyard, Flitwick and Husborne series as described for other fields (Catt *et al.*, 1977). The distribution of Cottenham series and the three heavier soils combined was determined by particle size analyses of subsurface samples (40–60 cm depth) taken by augering at each 10 m grid intersection over the whole field, Cottenham series occurring where the subsurface texture is sand or loamy sand (% silt+2(% clay) ⩽ 30). Flitwick and Stackyard series were distinguished by the presence and absence respectively of mottled (gleyed) horizons within 70 cm of the surface (determined during hand augering), both series having a wide range of subsurface particle size distribution (% silt+2(% clay) = 30·1 to >70). Husborne series is mapped where Chalky Boulder Clay occurs in the subsoil, the subsurface horizon also being gleyed within 40 cm of the surface and containing more clay and silt than most of the Stackyard and Flitwick soils.

Flitwick series is restricted to low-lying parts of the field near the north-east corner (Fig. 1), where the colluvial deposits are generally thicker and heavier in texture (% silt+2(% clay) = 50 to 84) than elsewhere. A borehole made by percussion drill in early August 1979 at the point marked X in Fig. 1 penetrated 1·6 m of gleyed colluvium and reached the water-table in the Lower Greensand at 6·7 m depth (87·7 m OD). Mottling due to gleying disappeared below about 2·0 m depth, probably because reduction of iron is dependent upon organic matter, which is absent at depth in the Lower Greensand. As it is unlikely that the water-table rises in winter by as much as 6 m above the August level, the gleying in the Flitwick soils probably dates from an earlier period when the water-table was several metres higher than at present. The finer textured colluvium in this minor SSW–NNE valley might then have been deposited partly by a temporary stream, tributary to the Crawley Brook.

Stackyard series occurs mainly on the floors of other shallow valleys revealed by the detailed topographic contours, and Cottenham series mainly occupies the intervening ridges and hillocks. The Stackyard soils are formed from colluvium (with % silt+ 2(% clay) > 30), which is >40 cm but generally <1 m thick over Lower Greensand. Husborne series occurs only in a small area adjacent to the south-western margin of the field. However, the occurrence of stony surface horizons with glacial erratics (probably remnants of the thin glacial gravel noticed beneath the Chalky Boulder Clay elsewhere on the farm) in other areas suggests the till was once more extensive, and has been removed by erosion. The present land surface was largely excavated through the till and into Lower Greensand probably during the most recent (Devensian) period of widespread periglacial surface erosion. The Cottenham, Stackyard and Flitwick soils are thus likely to be no older than early Flandrian (i.e. <10 000 years), and may well be much younger.

Profile characteristics

Field morphology. Appendix A gives brief profile descriptions of six monoliths representing the four soil series on Stackyard, which were extracted with the Proline corer at the sites numbered in Fig. 1. Lower Greensand was penetrated at varying depths in all six monoliths, and consists of loose sand or loamy sand of rather variable colour (brown, grey, brownish grey, yellowish brown, reddish brown, yellowish red, olive, olive-brown, etc.). Horizontal colour banding and irregular mottling are both common, and thin layers of grey clay or hard, reddish brown sandy ironstone (carstone) are sometimes encountered. All the overlying soil horizons are heavier in texture (sandy loam to clay), and most are uniform brown or dark brown in colour, are slightly stony, and have weakly developed coarse to medium subangular blocky structure.

In profile 1 (Cottenham stony phase), unaltered Lower Greensand was encountered at 70 cm, and the sandy loam Ap and Bw horizons were separated from this by a very stony horizon of brown loamy sand at 34–70 cm depth, probably composed of Lower Greensand mixed with glacial gravel originally deposited beneath the Chalky Boulder Clay. As more than half the upper 80 cm is sand or loamy sand, the profile is placed in the Brown sand group of Avery (1973), even though the Quaternary sediment over the Lower Greensand is thicker than in most other Cottenham soils on the field. A similar stony phase forms several other small patches (e.g. on the northern flank of the knoll near the north-west corner of the field), but in most of the Cottenham soils less stony sandy loam horizons overlie unaltered Lower Greensand at <40 cm depth.

In the three cores of the Stackyard series (profiles 2, 3 and 4), Lower Greensand occurred at depths of 115, 166 and 134 cm respectively. Dark brown Ap horizons overlie uniform brown or dark brown Bw, Bt or BC horizons of sandy loam texture in profiles 2 and 3, and mottles resulting from drainage impedance are absent from at least the top metre. In profile 4 a few diffuse reddish brown mottles occurred in the Bw horizon just beneath the plough layer; these probably result from frequent but temporary surface flooding, as the profile is near the lowest point on the western side of the field, in an area that receives much runoff during heavy rain. The soil is consequently an intergrade to the Flitwick series, though we group it with the Stackyard because beneath the Bw horizon mottling due to poor drainage recurs only at 129 cm. The faint yellowish brown mottles occurring below 70 cm in all three profiles probably result from faunal activity (see p. 13).

Below the surface, sandy loam textures persist to 115 cm in profile 2, 154 cm in profile 3 and 92 cm in profile 4. Thin horizons of rather heavier texture at or near the base of the colluvium (e.g. the 2Cu2 horizon of profile 3) are fairly common in the Stackyard series, but the more complex stratification of sandy and loamy layers exemplified by the deep subsoil (Cu(g)) horizons of profile 4 is a more local feature. These textural variations in the older colluvial layers probably record environmental changes in the early history of

TABLE 1

Particle size distributions at whole ϕ intervals ($\phi = -\log_2$ mm) of soil samples from profiles in Stackyard Field, Woburn Experimental Farm (weight percentages of oven-dry, peroxidised soil < 2 mm)

Size fractions (μm)	φ Equivalent	Profile	1. Cottenham (SP 94953425)				2. Stackyard (SP 94963428)							3. Stackyard (SP 95023416)						
		Horizon Depth (cm)	Ap 0–22	Bw 22–34	Cu 34–70	2Cu 70–87	Ap 0–23	Bw 23–42	Bt1 42–72	Bt2 72–91	Bt3 91–109	Bt4 109–115	2Cu 115–175	Ap 0–19	Bw 19–51	BC 51–78	Cu(g) 78–108	2Cu1 108–154	2Cu2 154–166	2Cu3 166–180
1000 to 2000	0 to −1		3·1	5·1	6·7	0·3	0·9	1·3	2·5	2·4	1·1	3·0	0·0	1·2	1·3	1·3	4·8	0·1	0·0	0·0
500 to 1000	+1 to 0		4·6	4·2	6·3	0·6	2·1	2·7	3·1	2·7	2·1	3·9	0·3	2·8	2·7	2·5	5·0	0·6	2·0	0·9
250 to 500	+2 to +1		17·9	18·3	24·0	12·3	12·7	14·2	14·2	15·5	16·4	14·7	8·0	17·6	15·0	14·5	19·0	8·7	22·8	15·3
125 to 250	+3 to +2		40·7	40·3	42·8	71·6	36·2	38·5	37·3	36·9	44·3	50·1	77·3	39·5	36·6	32·4	40·3	65·8	46·9	63·4
63 to 125	+4 to +3		4·5	5·0	4·7	6·5	4·7	4·9	4·6	4·4	5·2	5·8	6·2	5·0	5·0	4·0	6·3	7·9	6·3	6·8
32 to 63	+5 to +4		4·9	4·4	3·4	0·8	6·0	6·0	6·4	5·9	9·6	5·8	0·3	6·3	4·7	10·8	4·9	0·3	0·5	0·6
16 to 32	+6 to +5		4·8	5·2	2·7	0·4	8·0	6·4	6·3	9·6	7·3	3·6	0·1	6·9	10·8	4·8	3·2	0·5	0·4	0·6
8 to 16	+7 to +6		3·5	3·2	1·5	0·5	5·3	4·4	4·2	5·2	4·1	2·0	0·2	4·1	5·7	11·5	1·8	0·7	0·5	0·1
4 to 8	+8 to +7		2·5	1·7	1·0	0·4	3·9	2·8	2·9	2·8	1·5	1·0	0·3	2·7	3·1	3·4	1·3	0·4	0·5	0·5
2 to 4	+9 to +8		1·9	1·9	0·9	1·1	3·8	2·9	2·5	2·5	2·0	1·2	0·4	2·2	2·8	2·5	1·1	0·8	0·9	0·6
<2	> +9		11·6	10·7	6·0	5·5	16·4	15·9	16·0	12·1	6·4	8·9	6·9	11·7	12·3	12·3	12·3	14·2	19·2	11·2

Size fractions (μm)	φ Equivalent	Profile	4. Stackyard (SP 95033447)										
		Horizon Depth (cm)	Ap1 0–7	Ap2 7–17	Bw 17–40	BC 40–73	Cu 73–92	Cu(g)1 92–112	Cu(g)2 112–115	Cu(g)3 115–129	Cu(g)4 129–134	2Cu1 134–144	2Cu2 144–180
1000 to 2000	0 to −1		0·4	1·1	0·7	0·6	0·8	0·2	0·0	0·1	0·2	0·0	0·0
500 to 1000	+1 to 0		2·0	2·6	2·3	1·8	1·6	1·5	1·0	0·7	2·2	0·3	0·3
250 to 500	+2 to +1		14·1	14·5	14·4	12·9	13·7	23·4	12·3	11·0	9·9	8·4	5·9
125 to 250	+3 to +2		48·0	45·4	45·3	44·9	42·8	64·0	66·8	70·5	62·8	76·6	78·4
63 to 125	+4 to +3		4·3	4·4	4·8	4·6	4·3	3·1	3·4	5·0	4·8	4·7	5·9
32 to 63	+5 to +4		4·3	5·9	5·4	7·0	10·3	0·8	0·1	0·2	0·3	0·3	0.4
16 to 32	+6 to +5		5·3	4·8	5·5	6·9	8·8	0·4	0·2	0·4	0·6	0·2	0·2
8 to 16	+7 to +6		3·5	3·7	4·1	4·4	4·6	0·4	0·6	0·4	0·8	0·0	0·2
4 to 8	+8 to +7		2·5	2·4	2·4	2·5	2·3	0·4	0·0	0·8	0·5	0·6	0·2
2 to 4	+9 to +8		1·9	2·1	2·2	2·0	1·9	0·4	0·9	0·3	1·0	0·7	0·9
<2	> +9		13·7	13·1	12·9	12·4	8·9	5·4	14·7	10·6	16·9	8·2	7·6

Size fractions (μm)	φ Equivalent	Profile	5. Flitwick (SP 95253458)										6. Husborne (SP 94973415)							
		Horizon Depth (cm)	Ap1 0–7	Ap2 7–33	Bw1 33–45	Bw2 45–61	Bt(g)1 61–69	Bt(g)2 69–89	2Cug1 89–114	2Cug2 114–144	2Cug3 144–169	2Cug4 169–177	Ap1 0–12	Ap2 12–25	Btg 25–39	2BCtg 39–68	3Cg 68–100	4C1 100–122	4C2 122–138	4C3 138–180
1000 to 2000	0 to −1		0·4	0·8	1·0	1·4	1·1	0·8	0·5	0·1	0·0	0·2	1·1	1·7	1·4	0·4	1·3	0·3	1·9	0·0
500 to 1000	+1 to 0		1·8	2·1	2·3	1·9	2·5	1·6	1·2	0·4	0·3	2·6	3·1	3·3	4·5	1·2	2·9	10·7	8·2	0·9
250 to 500	+2 to +1		12·4	15·2	13·3	13·7	13·1	12·2	15·3	10·9	11·0	23·2	16·3	14·6	19·0	5·0	12·6	50·7	23·9	11·7
125 to 250	+3 to +2		36·6	37·2	35·9	36·1	35·8	32·1	66·2	75·7	72·0	58·2	39·5	37·0	36·4	11·6	31·8	25·4	36·3	66·3
63 to 125	+4 to +3		3·7	4·0	4·5	4·1	4·3	4·2	3·4	3·1	4·4	2·2	6·2	6·3	5·1	4·7	6·1	2·0	9·4	8·5
32 to 63	+5 to +4		7·3	7·7	8·3	8·8	10·5	11·9	1·2	0·2	0·1	0·1	5·0	5·0	4·2	3·6	3·4	0·7	7·1	0·9
16 to 32	+6 to +5		9·0	7·8	8·3	9·2	10·2	12·8	0·8	0·1	0·4	0·1	4·6	5·8	2·8	5·9	3·4	0·3	2·2	0·3
8 to 16	+7 to +6		5·9	4·9	5·5	5·6	5·8	6·5	0·5	0·2	0·3	0·3	3·8	4·5	2·8	4·7	3·1	0·1	0·8	0·1
4 to 8	+8 to +7		4·2	3·3	3·6	3·8	3·1	3·7	0·5	0·2	0·4	0·4	2·8	3·2	2·5	6·2	3·2	0·1	0·3	0·2
2 to 4	+9 to +8		2·4	2·5	2·3	2·5	2·7	2·0	0·6	0·4	0·3	0·5	2·6	2·4	2·1	6·1	3·4	1·1	1·1	1·2
<2	> +9		16·3	14·5	15·0	12·9	10·9	12·2	9·8	8·7	10·8	12·2	15·0	16·2	19·2	50·6	28·8	8·6	8·8	9·9

deforestation and primitive agriculture in the area, whereas the more homogeneous (sandy loam) upper colluvial layers have probably accumulated mainly since the advent of mechanical cultivation techniques.

Profile 5 (Flitwick series), from the low-lying north-eastern part of the field, is fairly strongly gleyed, with common ochreous, olive or grey mottles from 61 cm downwards. Colluvium of uniform sandy loam texture overlies gleyed Lower Greensand at 89 cm depth, but elsewhere in this corner of the field the colluvium (possibly with some alluvial layers) is thicker and heavier in texture towards the base.

Like almost all the other soils on Stackyard field, the Husborne series (profile 6) has a dark brown, slightly stony, sandy loam plough layer, probably composed of colluvium. However, this overlies a strongly mottled B horizon of sandy clay loam texture, which in turn rests at 39 cm depth on a thin layer of Chalky Boulder Clay (2BCtg horizon). The depth to boulder clay is much less than in most of the soils mapped as Husborne series on School Field (Catt *et al.*, 1977), and the firm, stony Head deposit overlying the till on School Field is either absent on Stackyard or represented only by the thin mottled Btg horizon. The boulder clay is separated from the Lower Greensand at 100 cm depth by a mottled, slightly stony, sandy clay loam (3Cg horizon), probably formed by subglacial mixing of the glacial detritus with surface layers of the Lower Greensand.

Particle size distribution (Table 1). The particle size distributions of samples from each horizon in the six monoliths was determined at whole ϕ intervals ($\phi = -\log_2$ mm) by sieving and the pipette sampling technique, after dispersion by overnight shaking in a dilute solution of sodium hexametaphosphate made alkaline by the addition of sodium carbonate.

Seventeen of the deeper subsoil samples corresponded to almost unaltered Lower Greensand, and these contained 5·4–19·2% clay (mean 10·6%) and 1·1–3·6% total silt in the 4–9 ϕ (63–2 μm) range (mean 2·2%). Catt *et al.* (1975) reported similar amounts of clay and silt in other Lower Greensand samples from the Woburn area. The sand fractions (−1–4 ϕ, 2000–63 μm) of the 17 samples are moderately well sorted, with 69·7–87·4% by weight in the 1–3 ϕ (500–125 μm) range, and the mode usually in the 2–3 ϕ (250–125 μm) range. The one sample of Chalky Boulder Clay analysed (the 2BCtg horizon of the Husborne profile) also had a similar particle size distribution to the boulder clay samples studied by Catt *et al.*, except that its clay content was rather greater. Apart from the large clay content and a small mode in the 2–3 ϕ sand, which is probably due to incorporation of some Lower Greensand in the glacial detritus, the boulder clay has a fairly even distribution of particles between all the ϕ units finer than −1 (2 mm).

The clay content of the 24 soil horizons overlying the Lower Greensand in profiles other than the Husborne ranges from 6·0 to 16·4% (mean 12·3), and is not significantly different from that of the Lower Greensand itself. In contrast, the silt content of these horizons is much greater than that of the Lower Greensand, ranging from 9·5 to 36·9% (mean 23·5). As in Stackyard and Flitwick profiles elsewhere on the farm (Catt *et al.*, 1975), this additional silt is mainly coarse silt (6–4 ϕ, 16–63 μm), but is not so well sorted as loess and is probably derived ultimately from the Chalky Boulder Clay. Because of the increased silt content, the total sand percentages are smaller than in the Lower Greensand, but the size distribution of the sand is essentially the same, so the process responsible for incorporation of silt selectively separated from the boulder clay did not detectably affect the sand component.

In the Husborne profile only one horizon apart from the Chalky Boulder Clay contains significantly more clay than the Lower Greensand; this is the 3Cg horizon, which is probably a mixture of Lower Greensand and unsorted boulder clay material. The 4C horizons below this have particle size distributions resembling the Lower Greensand. Horizons above the Chalky Boulder Clay layer are mixtures of Lower Greensand with varying proportions of silt from the boulder clay.

Organic carbon. This was measured in selected horizons of profiles 1–5 inclusive by the wet oxidation (Tinsley III) method of Kalembasa and Jenkinson (1973). Table 2 gives the results.

Amounts of organic C in the surface (Ap) horizons range from 0·96 to 3·12%. As all profiles were taken from long-established grass headlands, it is unlikely that this range reflects recent land use. There is no correlation with clay content, but the largest amount is in the Flitwick profile, where poor drainage may have partly inhibited oxidation. However, the range in the better drained Cottenham and Stackyard profiles is almost as large, so it is likely that the variations are largely inherited from earlier differences in land use (probably before the field was taken over for experimental purposes in 1876). The larger values may reflect in part localised incorporation of coal or charcoal in the topsoil (see p. 20), as noted originally by Crowther (1936, 319).

In the Cottenham and Stackyard profiles amounts of organic carbon fall sharply beneath the Ap horizon to 0·5–0·8%, and then generally decline less rapidly with depth through the loamy horizons derived from colluvium. However, in profile 3 the downward decrease is temporarily reversed at a depth of 108 cm. In the Flitwick profile there is a steady decrease downwards, but each horizon contains considerably more organic C than those at equivalent depths in the better drained profiles. In all five profiles the transition from colluvium to Lower Greensand is marked by a further sharp decrease to 0·3–0·7% organic C.

TABLE 2

Organic carbon contents of soil profiles from Stackyard Field, Woburn Experimental Farm

Profile No.	Series	Horizon	Depth (cm)	Weight % organic C
1. (SP 94953425)	Cottenham	Ap	0–22	1·60
		Bw	22–34	0·48
		Cu	34–70	0·29
		2Cu	70–87	0·07
2. (SP 94963428)	Stackyard	Ap	0–23	1·29
		Bw	23–42	0·80
		Bt1	42–72	0·54
		Bt3	91–109	0·22
		2Cu	115–175	0·03
3. (SP 95023416)	Stackyard	Ap	0–19	0·96
		Bw	19–51	0·49
		BC	51–78	0·28
		2Cu1	108–154	0·35
		2Cu3	166–180	0·07
4. (SP 95033447)	Stackyard	Ap1	0–7	2·95
		Ap2	7–17	1·24
		Bw	17–40	0·85
		Cu	73–92	0·32
		Cu(g)2	112–115	0·12
		Cu(g)4	129–134	0·12
		2Cu2	144–180	0·07
5. (SP 95253458)	Flitwick	Ap1	0–7	3·12
		Ap2	7–33	1·68
		Bw1	33–45	1·29
		Bt(g)1	61–69	0·89
		2Cug1	89–114	0·36
		2Cug3	144–169	0·04

Micromorphology. Thin sections 25–30 μm thick, 7·5 cm long and 6·5 cm wide were cut from blocks of soil representing the main horizons of profiles 2 (Stackyard series), 5 (Flitwick) and 6 (Husborne). The blocks were extracted from central parts of the Proline cores by pressing open-ended rectangular tins (Kubiena boxes) into the moist soil during careful dissection of the monoliths, avoiding deformed soil near the circumference of the cores as much as possible. The blocks were dried by acetone replacement, and impregnated with Crystic polyester resin; other preparative details are given by Bascomb and Bullock (1974). Appendix B gives brief descriptions of the sections and an explanation of the terminology used, which is based on Brewer (1964) and Bullock and Murphy (1976, 1979). Thin sections provide specific information on the extents of clay illuviation, soil disturbance (e.g. by faunal activity), hydromorphic segregation of iron and manganese, weathering of silt and coarser particles, and heterogeneity of horizons (e.g. of particle size distribution or mineralogy). They also allow the size, shape and abundance of pores to be measured, and the nature of discontinuities (e.g. boundaries between horizons) to be investigated.

In profile 2 (Stackyard series), the amounts of illuvial clay between 42 and 91 cm depth would be sufficient ($>2\%$ estimated by area) to place the soil in the typical argillic brown earth subgroup of Avery (1973), if the total clay contents of these horizons were also significantly greater than those of the overlying Ap and Bw horizons. However, clay contents decrease downwards (Table 1), so the argillic (Bt) horizons cannot be used as diagnostic horizons of an argillic group or subgroup, and the profile is placed in the brown earth (*sensu stricto*) group. The recent unpublished revision of Avery's classification distinguishes brown earths in colluvium >40 cm thick at subgroup level as 'colluvial brown earths', and the Stackyard series is shown as such in Fig. 1. Similarly, illuvial clay is fairly common in the Bt(g)2 horizon (69–89 cm) of the Flitwick profile, but the total clay content of this horizon is less than that of any above except the thin horizon (61–69 cm) immediately overlying it; the profile is therefore classed as a gleyic brown earth rather than a gleyic argillic brown earth. These Bt horizons are relatively clay-poor despite their illuvial enrichment probably because of original heterogeneity of the colluvium in which the Stackyard and Flitwick series are developed. In contrast, the Husborne profile qualifies as an argillic subgroup (typical argillic stagnogley soil) on the grounds of both sufficient illuvial clay concentrations (in horizons between 25 and 68 cm depth) and the larger amounts of total clay in these horizons compared with those above. However, the increased clay content, especially of the lower illuvial horizon (39–68 cm), which is composed of Chalky Boulder Clay, reflects parent material inhomogeneity much more than illuvial enrichment, though illuvial concentration may explain why this horizon contains slightly more clay than typical Chalky Boulder Clay. As it still contains chalk fragments, the boulder clay layer is designated a BC horizon, but the clay matrix contains much less carbonate (0·3%) than is usual in Chalky Boulder Clay, and must have been partly decalcified. The occurrence of both void clay coatings and intrapedal clay concentrations in this horizon shows that after decalcification it was subjected to some disturbance.

Extensive faunal disturbance is evident to depths of at least 87 cm in the Stackyard profile, 81 cm in the Flitwick and 39 cm in the Husborne. It results in a degree of heterogeneity within horizons that is not revealed by the particle size and other analyses of bulk samples. Smoothed channels and chambers, often partly filled with faecal pellets, are common in higher horizons, and in subsoil horizons of the Flitwick profile irregular patches noticeably richer in clay and organic matter than the surrounding soil have been brought down from the Ap horizons. However, not all the faunal activity recognised in the thin sections is necessarily contemporary or very recent. As layers of colluvium have been built up by repeated soil erosion since deforestation in the Bronze Age or possibly earlier periods, successive land surfaces have been buried increasingly deeply. In the Stackyard profile, the Bt2 horizon (72–91 cm), which has a sandy loam texture overall, contains irregular patches up to 15 mm across composed of sand grains enveloped in illuvial clay. These were recognised as very fine, yellowish brown mottles during macroscopic examination of the profile (Appendix A), and possibly originated as fragments of a Bt horizon developed previously in the Lower Greensand, which were incorporated by faunal mixing into the earliest layers of colluvium.

Hydromorphic features such as ferruginous and ferrimanganiferous segregations and nodules are most evident in the Husborne and Flitwick profiles, even as high as the Ap horizons, where the macroscopic evidence for irregular distribution of iron and manganese is obscured by organic matter and agroturbation (mixing by soil cultivation). Weaker hydromorphic features, which were also undetected macroscopically, occur in the Stackyard profile but only below 53 cm depth.

The only evidence for mineral weathering obtained from the thin sections is the irregular oxidation of green glauconite grains to orange or brown aggregates containing hydrated iron oxides ('limonite'). However, these are randomly distributed through all horizons examined of the three profiles, and their alteration probably predates deposition of the colluvium. Further slight alteration in the present profiles is suggested in some subsoil horizons, where partial disintegration of some grains of all colours has occurred. Similar disintegration may also have occurred in Ap horizons, but there the resulting clay and silt particles would have been dispersed by cultivation and disturbance of the soil.

Micromorphometry of pores in Stackyard profile 2. We attempted to estimate more precisely the size distribution of pores in one of the profiles (Stackyard profile 2, SP 94963428), using the Quantimet image analysing computer (Murphy *et al.*, 1977). Triplicate thin sections were cut for each of the main horizons, and an internal area of each section measuring 4·6 × 3·6 cm (to avoid edge disturbance) was photographed at two magnifications, and measurements made on the resulting prints. For each horizon the total area scanned was therefore 13·8 × 3·6 cm (49·68 cm^2).

The smallest pores measured by this technique are 28 × 28 μm (784 μm^2), the size of a single picture point at the higher magnification used, and these appear in the smallest size class used (600–1250 μm^2). Total pore area in this class is therefore underestimated. Adequate representation of the largest pores measurable in the thin sections is also impossible, because of the limited area scanned. The upper size limit of pores adequately represented by measurements over approximately 50 cm^2 is probably 2000 × 2000 μm (based on B.S. 812:1960, Table 5). The pore area range over which this technique gives reliable results is therefore about 1250–4 000 000 μm^2.

Assuming that percentage areas in the thin sections correspond to volumetric proportions, as maintained by Chayes (1956) and others, the total volume of pores with areas between 1250 and 4 000 000 μm^2 ranged from 3·3% at the Bt4–2Cu boundary (111–119 cm depth) to 8·1% in the Bt1 horizon (sectioned at 53–61 cm depth). The volume decreased regularly both upwards from the Bt1 horizon to the topsoil and downwards to the Lower Greensand. In the Bt2 horizon (sectioned at 79–87 cm) no pores larger than 5×10^6 μm^2 were detected, but in other horizons they totalled 4·8–10·3%. For the reason given above, these percentage volumes of larger pores are not very precise, but their general size distributions are interesting. The horizon with the largest total volume of pores $> 5 \times 10^6$ μm^2 area is the 2Cu, but in this no pores $> 1{\cdot}6 \times 10^8$ μm^2 were detected. In horizons above the Bt2 the measured volume of pores $> 5 \times 10^6$ μm^2 area increased upwards from 4·8% in the Bt1 horizon to 7·0% in the Ap, and these pores are considerably larger on average in the Ap horizon, where 46% of the total pore

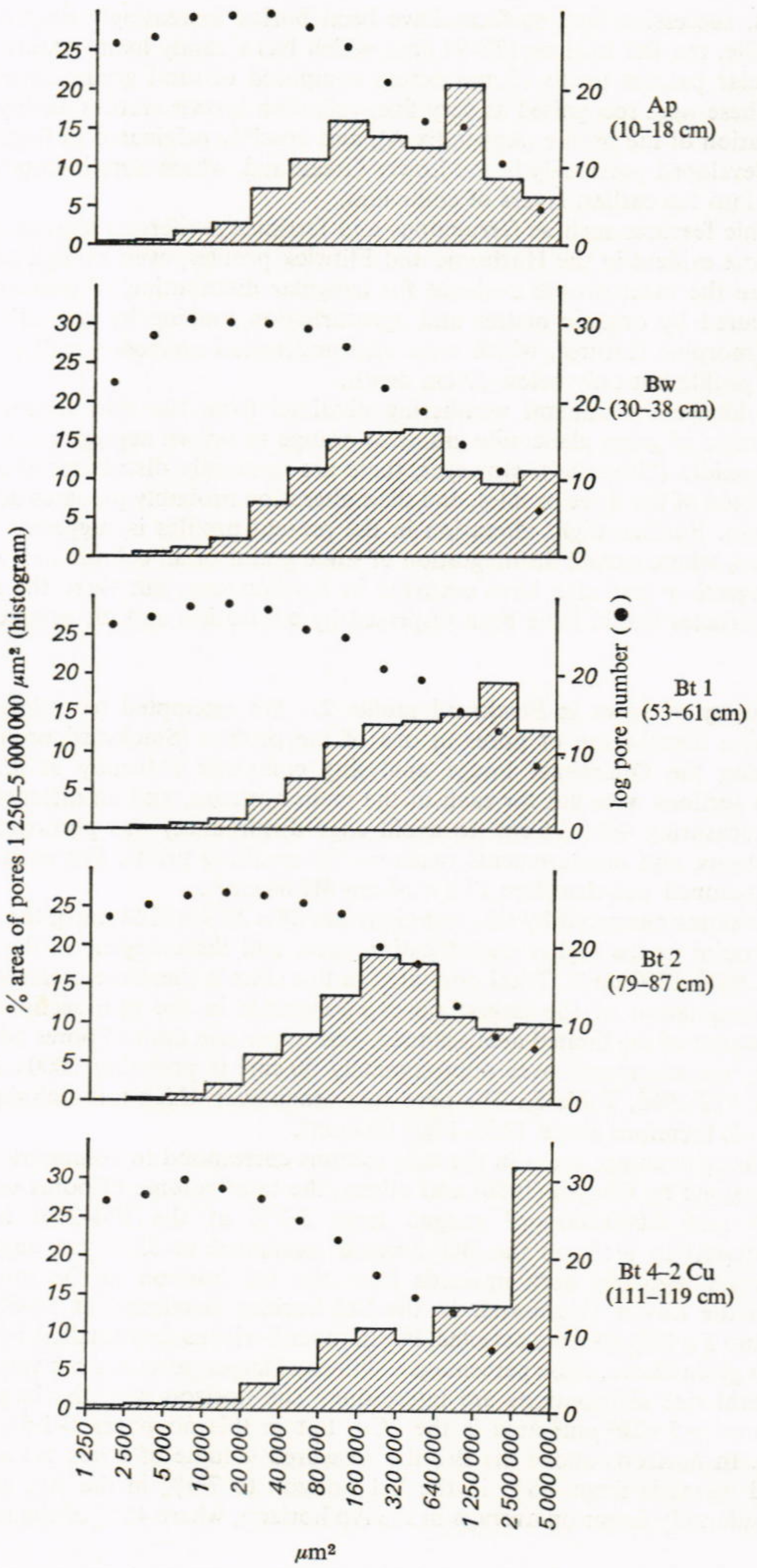

FIG. 2. Size distribution (as histogram) and numbers (as spots) of pores between 1250 and 5×10^6 µm area in Stackyard profile 2.

area measured was attributable to pores $>1{\cdot}6\times10^8$ μm^2, than in the Bw and Bt1 horizons, in which no pores $>8\times10^7$ μm^2 were encountered.

Within the range over which the pore size measurements are reliable (1250–4 000 000 μm^2), there is a tendency for pores to become coarser downwards, with the exception of the Bt2 horizon, which has finer and also fewer pores than any of the horizons studied (Fig. 2). Taken with the above observations on coarser pores, this suggests that differences in pore size distribution through the profile result from the interaction of several processes. In the lowest horizons studied (Bt4–2Cu) most of the pores result from simple packing of the sand particles; the lack of clay and silt (especially in the 2Cu horizon) is the main reason why there are relatively few pores $<640\,000$ μm^2, and the scarcity of faunal activity explains the absence of very large pores ($>1{\cdot}6\times10^8$ μm^2). In higher horizons the increasing range of pore size results partly from the larger amounts of silt and clay (giving more small pores), and partly from extensive rearrangement of soil particles by root growth, faunal activity and clay illuviation. In the Bt2 horizon, the small mean pore size and absence of pores $>5\times10^6$ μm^2 result in a smaller total measured pore volume (5·2%) than in any other horizon (11·5–13·7%). This probably reflects the combined effects of pore infilling by illuvial clay and diminished root penetration and faunal disturbance compared with higher horizons. Larger voids resulting from cultivation are absent from the topsoil, because profile 2 was taken from a long established grass headland.

Further comment on these results is impossible at present because of the lack of comparative results for other profiles at Woburn and elsewhere. However, it is clear that the technique quickly provides information on pore size distribution, but which is reliable only over a limited size range. The irregular distribution of larger pores resulting, for example, from faunal activity in higher soil horizons causes difficulties in the determination of total pore space. More and/or larger thin sections would only increase slightly the range of reliable measurements, and a different technique is therefore required to measure voids in very coarsely structured soils.

Soil texture variation

All the main soil series on Stackyard (Cottenham, Stackyard and Flitwick) show considerable variation in subsoil and, to a lesser extent, topsoil texture. Bulked topsoil (0–25 cm) samples were taken at 20 m grid intersections over the whole field, and subsurface (40–60 cm) samples at 10 m intervals, and the amounts of clay (<2 μm), total silt (2–63 μm), total sand (63–2000 μm) and stones (>2000 μm) in each were determined by sieving and the pipette sampling technique after peroxidation to remove organic matter and dispersion by overnight shaking in dilute hexametaphosphate solution. The silt and clay percentages for subsurface samples were used to indicate approximately how much of the top 80 cm is sand or loamy sand in texture (silt $\%+2$(clay $\%$) $\leqslant 30$), and the distinction between Cottenham and the other two series (Fig. 1) was based on this. However, the overall range of silt $\%+2$(clay $\%$) is 24·3–59·1 for the topsoil samples and 12·9–107·1 for the subsurface samples. Soil texture below the surface in particular is more variable than the simple soil series map suggests, and as some important agricultural properties of the soils (e.g. water retention and release characteristics) depend partly on particle size distribution at and below the surface, the lateral variation in texture for the two levels at which we sampled is shown in Figs. 3 and 4.

Excluding the small area of Husborne series near the south-west border of the field, the areas with heaviest subsurface texture (Fig. 3) are in the north-east corner (approximately coincident with the area of Flitwick series), the south-east corner, and a small patch on the western side of the knoll near the north-west corner. Areas of Cottenham

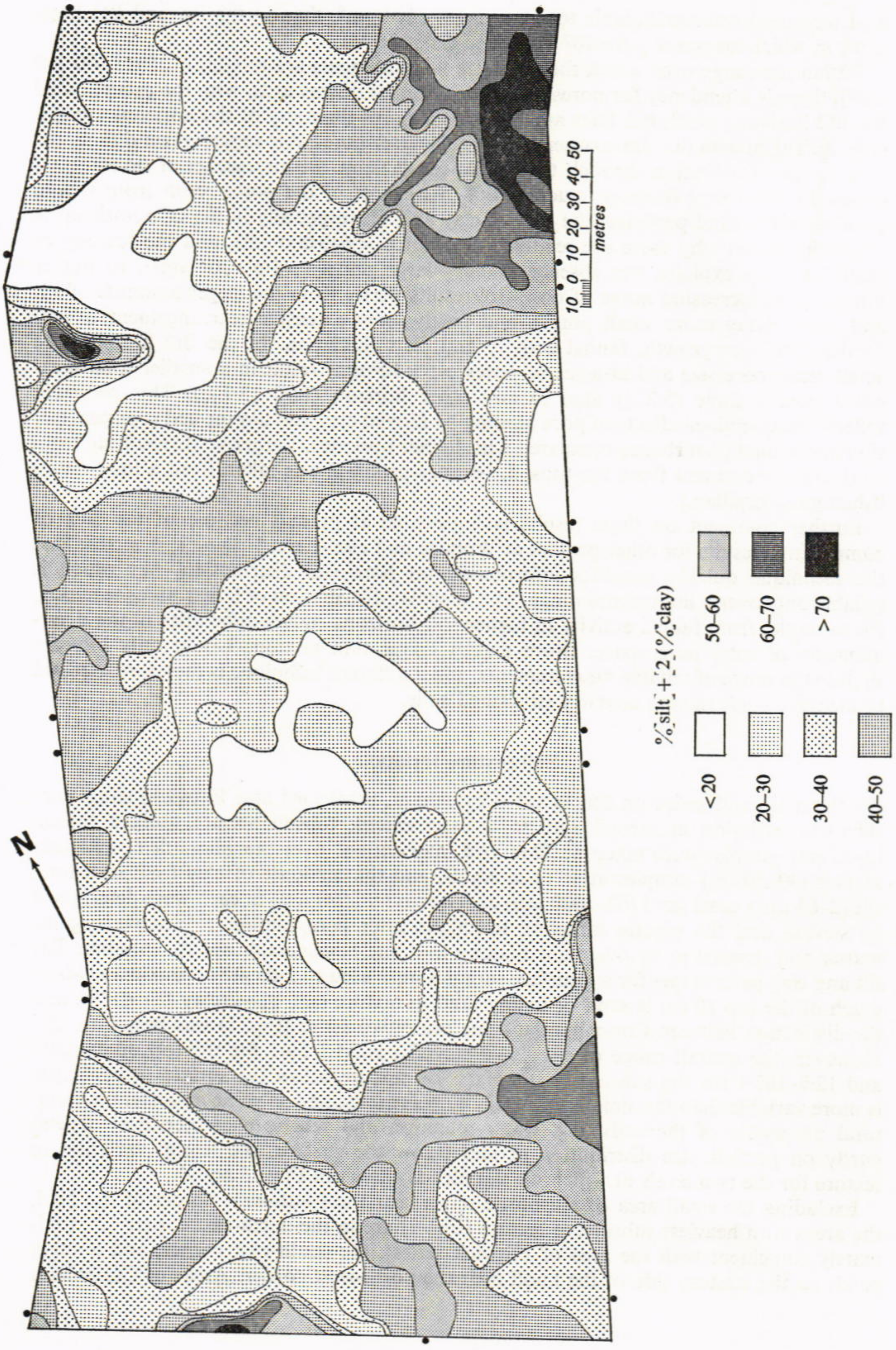

FIG. 3. Variation in subsurface (40–60 cm) texture (% silt + 2(% clay)) on Stackyard Field.

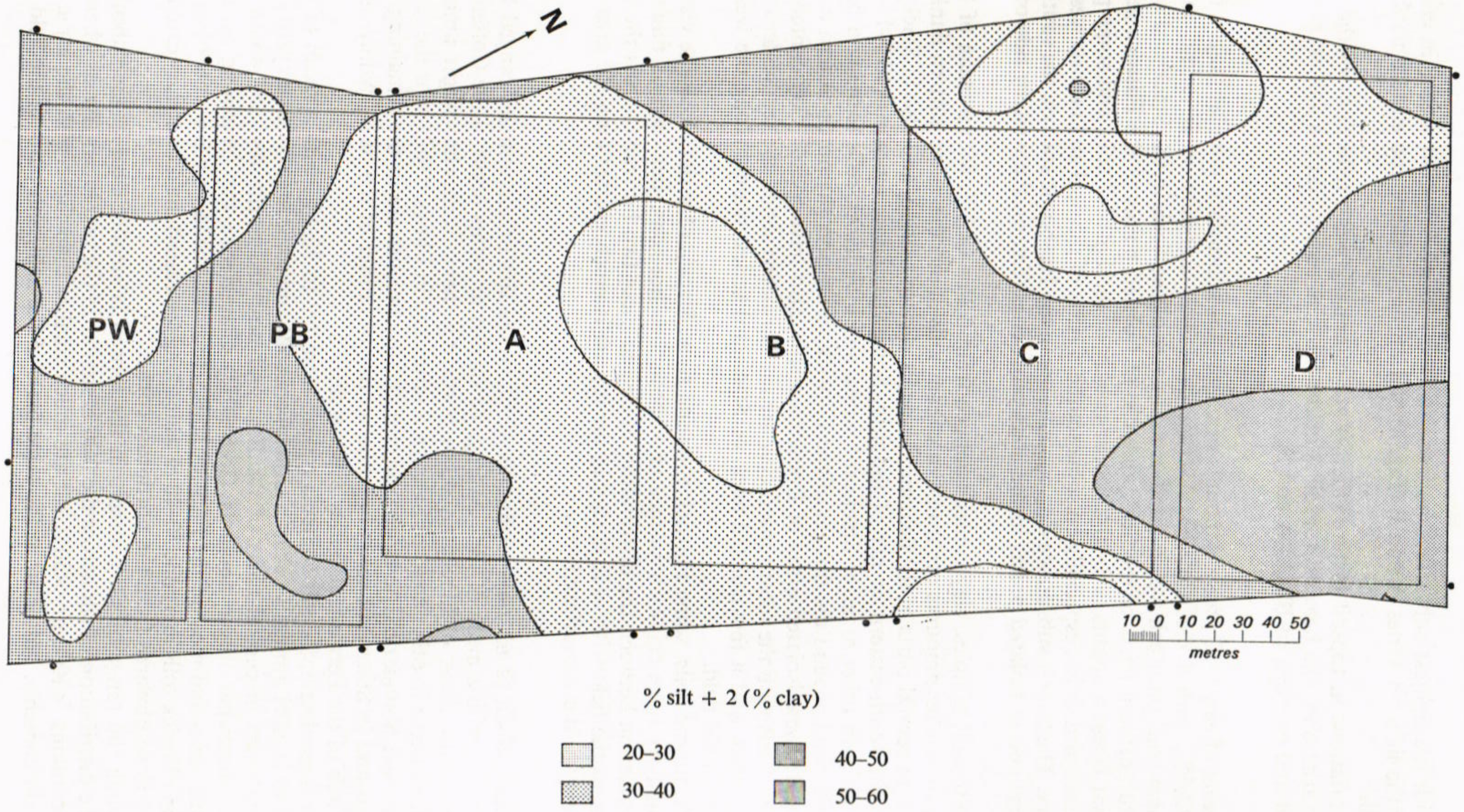

FIG. 4. Variation in surface (0–25 cm) texture (% silt+2(% clay)) on Stackyard Field, and boundaries of main experimental sites (Permanent Wheat (PW), Permanent Barley (PB) and Series A, B, C and D).

series with the lightest subsurface horizons (silt %+2(clay %) < 20) occur in central parts of the field on Series A and B (Fig. 4) and on the northern and eastern flanks of the knoll.

The variations in topsoil texture (Fig. 4) are essentially weak reflections of the subsurface variations. The heaviest topsoil is in the Flitwick series, and the lightest around the knoll and on parts of Blocks A and B.

Distribution of clay (<2 μm). Amounts of clay in the subsurface samples ranged from 3·4 to 42·6%, with a mean of 9·3. Average or smaller amounts occur mainly in the Cottenham soils on north-western and central parts of the field, in the Stackyard series mainly in northern parts of the field, and also at isolated points in the Flitwick series. Somewhat larger amounts (9·3–20%) occur mainly in the Flitwick soils and some parts of the Stackyard series, especially on some southern parts of the field and near its western boundary. The largest subsurface clay contents are in the Husborne soils on the southern boundary, and at isolated points in the Stackyard series (e.g. on the western side of the knoll).

In the topsoil samples, clay contents ranged from 6·8 to 19·3%, with a mean of 10·9. Average or smaller amounts occur in Cottenham soils on northern and eastern flanks of the knoll, in central parts of the field and along its eastern margin, and also in Stackyard series in the south-eastern corner of the field. Somewhat larger amounts (10·9–13·0%) occur mainly in other areas of Stackyard series, and in Flitwick soils forming a broad concentric band around the margin of the Flitwick series near the north-eastern corner of the field; some isolated areas of Cottenham soils also have topsoil clay contents in this range. Soils with the most topsoil clay are the Husborne series, the remainder of the Flitwick series, and a few isolated areas of Stackyard series, mainly along the western boundary of the field.

The Husborne soils, some Flitwick soils and some Stackyard series along the western field boundary have clay-rich surface and subsurface horizons, but there is otherwise little correlation between the distribution of clay in these two horizons across the field. The area of the field with >10% clay in the topsoil is much greater than the area with >10% clay in the subsurface layer.

Distribution of silt (2–63 μm). Amounts of silt in the subsurface samples ranged from 1·4 to 53·2%, with a mean of 18·5. Average or smaller amounts occur in the Cottenham soils and many areas of Stackyard series bordering them. Somewhat larger amounts (18·5–30%) occur in other areas of Stackyard series and in Flitwick soils near the central northern field boundary. The largest subsurface silt contents are in the remaining Flitwick soils and in Stackyard series near the south-east corner of the field (mainly on the eastern half of the Permanent Barley experiment).

In the topsoil samples, silt contents ranged from 6·2 to 32·4%, with a mean of 18·6. Average or smaller amounts occur in Cottenham soils and some areas of Stackyard series bordering them in central parts of the field and near the north-west and south-west corners. Somewhat larger amounts (18·6–30%) characterise the remaining areas of Stackyard series and most of the Flitwick soils. However, the largest amounts of topsoil silt are in Flitwick soils in a zone 30–40 m wide along the eastern field boundary extending about 60 m southwards from the north-east corner.

Although the range of silt contents in the topsoil is smaller than in the subsurface layer, the distribution of silt across the field is similar in the two layers. Areas where the topsoil contains <10% or >30% silt are much smaller than those with the same subsurface silt contents, but occur in the same parts of the field, and parts of the field with

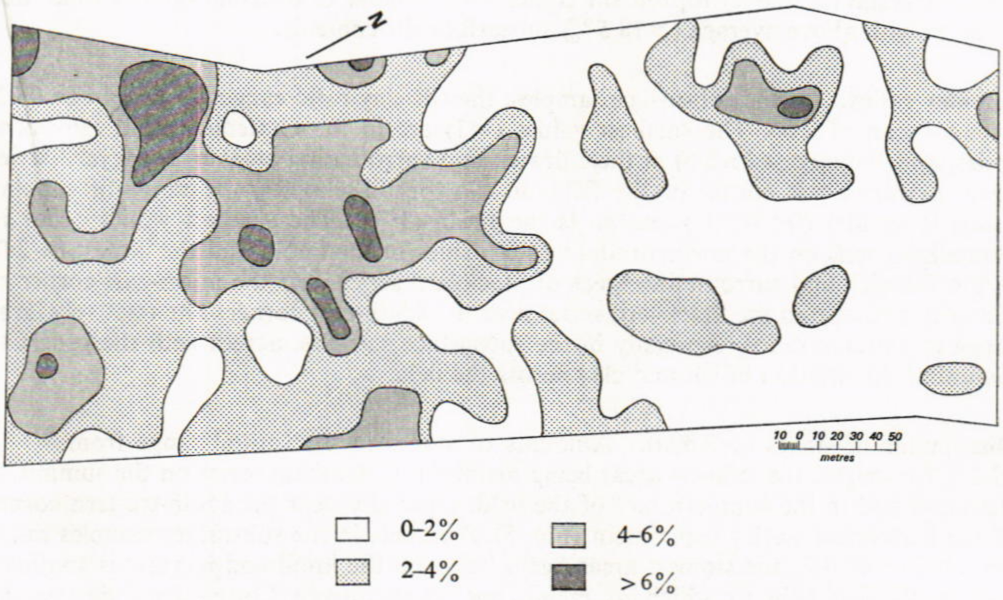

FIG. 5. Percentage stones (> 2 mm) in the surface soil (0–25 cm) of Stackyard Field.

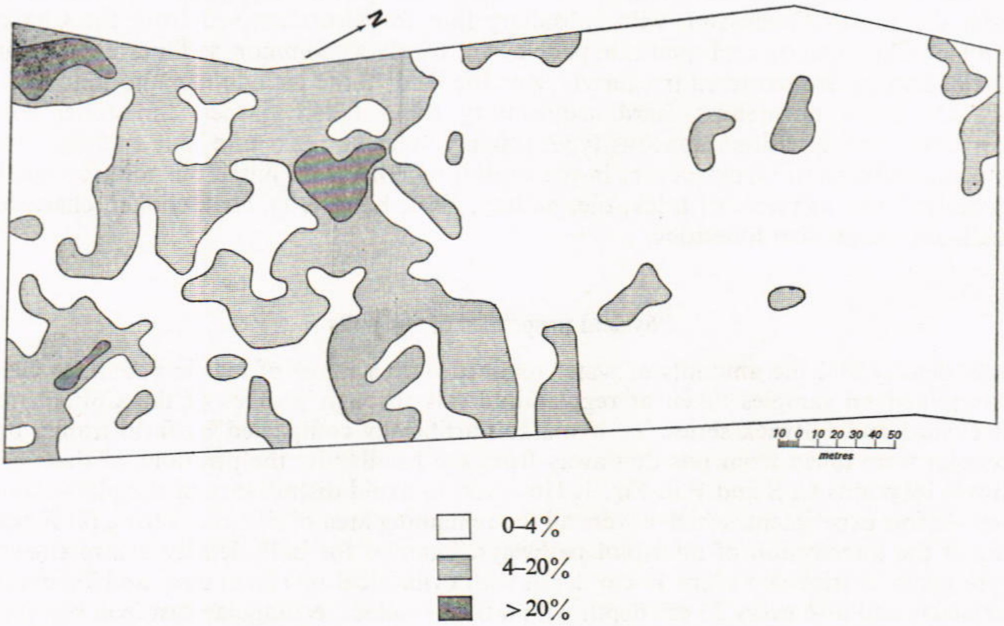

FIG. 6. Percentage stones (> 2 mm) in the subsurface soil (40–60 cm) of Stackyard Field.

above average (>18·6%) topsoil silt contents are similar in distribution and total area to those with above average (>18·5%) subsurface silt contents.

Silt/clay ratios. In the subsurface samples, the silt/clay ratio ranges from 0·14 to 9·02, with a mean of 2·04. The smallest values (<1) are in the Cottenham and Husborne series, and the largest (>3·5) in the Flitwick and surrounding areas of Stackyard series near the north-east corner of the field. In the topsoil samples, the range of silt/clay ratios is smaller (0·55–2·91) and so is the mean (1·70). The smallest values occur in Cottenham soils on the northern and western sides of the knoll, and the largest (>2·0) in the Flitwick and surrounding areas of Stackyard series near the north-east corner of the field, and also in the Stackyard series near the south-east corner. The relatively large range of silt/clay ratios, especially in the subsurface samples, agrees with the generally dissimilar distribution of silt and clay across the field.

Distribution of stones (>2 mm). Amounts of stones in the topsoil range from 0·3 to 22·2% by weight, the stoniest areas being mainly in Cottenham series on the summit of the knoll and in the southern half of the field, especially near the south-western corner of the Permanent Barley experiment (Fig. 5). Amounts in the subsurface samples range from 0·0 to 46·9%, the stoniest areas again being on the knoll and in various southern parts of the field (Fig. 6), which are mainly but not exclusively Cottenham series. As the stoniest horizons seem to rest directly on Lower Greensand, and are little influenced by the distribution of colluvium, they probably represent patches of glacial gravel originally underlying Chalky Boulder Clay. This is supported by the generally greater stone content of soils in the southern half of the field near to the only remaining (though admittedly small) patch of boulder clay. The large area of colluvium enclosing the Flitwick soils in the north-east corner of the field is in fact notably free of stones, especially in the subsurface horizon.

The stones in subsurface horizons are mainly sandy ironstone (carstone) fragments from the Lower Greensand, with subsidiary flint fragments derived from the Chalky Boulder Clay. Quartz and quartzite pebbles are nearly as common as flint, and various glacial erratics are scattered irregularly over the field; these include metamorphic rocks (schists, slates, hornfelses), hard sedimentary rocks (chert, jasper, limestone, conglomerate) and occasional igneous types (mainly volcanic rocks and pink granite). The same assemblage of stones occurs in the topsoil together with numerous anthropogenic additions, such as pieces of brick, tile, pottery, glass, bone, iron, coal, clinker, charcoal, chalk and magnesian limestone.

Physical properties of the soils

Bulk density and the amounts of water retained over a range of matric potentials were determined on samples taken at regular intervals through profiles of the Cottenham, Stackyard and Flitwick series. To avoid soil artificially compacted by farm traffic, the samples were taken from pits dug away from the headlands; the positions of these are shown by points C, S and F in Fig. 1. However, to avoid disturbance of the plots of the Ley–Arable experiment, which covers all the remaining area of Flitwick series, pit F was dug at the intersection of inter-plot pathways. Samples for bulk density measurements were taken in triplicate every 15 cm depth with cylindrical tins 5 cm deep and 7·5 cm in diameter, and also every 23 cm depth with a thick-walled, rectangular cast iron box (the Lawes box), which is 9 in. (23 cm approximately) deep and has a 6 in. (15 cm approximately) square cross section, and is driven into the soil with a large wooden rammer.

The samples from the tins were used for measurements of water retention at various matric potentials.

Bulk density. Table 3 gives the dry bulk density values obtained by dividing the oven-dry (105°C) weights of soil in the tins and Lawes box by the known volume of these containers. Those for the tins are means of the triplicate samples. Values for the Lawes box range from 1·45 to 1·77 g cm^{-3} with a mean of 1·59, whereas those for the tins range from 1·38 to 1·75 with a mean of 1·52; on average the box samples are 4·6% denser than those of the tins, though individual values for similar depths range from 15% greater to 2·5% less. These differences suggest a fairly systematic error between the two sampling methods. Because of the thickness of its walls, the Lawes box probably compresses the sample slightly, and for this reason the values obtained from the samples from the tins are preferred.

In all three profiles samples from near the surface are slightly denser than those from deeper layers. This difference is greatest in the Flitwick profile, the surface layer of which

TABLE 3

Dry bulk densities (g cm^{-3}) of samples from profiles representing the main soil types on Stackyard Field, Woburn Experimental Farm (Fig. 1 shows the positions of profiles C, S and F)

Profile	Sample depth (cm)	Particle size class	Bulk density Lawes box	Bulk density Tin
C. Cottenham	0–23	loamy sand	1·59	
(SP 95093456)	5–10	loamy sand		1·50
	20–25	loamy sand		1·54
	23–46	loamy sand	1·68	
	35–40	loamy sand		1·55
	48–71	loamy sand	1·46	
	50–55	loamy sand		1·44
	65–70	loamy sand		1·44
	71–94	sand	1·53	
	80–85	sand		1·46
S. Stackyard	0–23	sandy loam	1·62	
(SP 95203445)	5–10	sandy loam		1·57
	20–25	sandy loam		1·56
	31–53	sandy loam	1·45	
	35–40	sandy loam		1·45
	53–79	sandy loam	1·52	
	50–55	sandy loam		1·38
	65–70	sandy loam		1·50
	81–104	sandy loam	1·59	
	80–85	sandy loam		1·52
	95–100	sandy loam		1·49
	104–127	loamy sand	1·53	
	110–115	loamy sand		1·57
F. Flitwick	0–23	sandy loam	1·77	
(SP 95243453)	5–10	sandy loam		1·75
	20–25	sandy loam		1·70
	23–46	sandy loam	1·55	
	35–40	sandy loam		1·50
	46–69	sandy loam	1·55	
	50–55	sandy loam		1·42
	65–70	sandy loam		1·50
	69–91	sandy loam	1·66	
	80–85	sandy loam		1·53
	91–114	sandy loam	1·73	
	95–100	sandy loam		1·50
	110–115	sandy loam		1·50
	114–137	loamy sand	1·66	

has a bulk density of 1·75 g cm^{-3}; this is probably because this profile was taken from a pathway and had consequently suffered more compression than the Cottenham and Stackyard profiles. A duplicate box sample taken from fallow soil close to site F had a bulk density (1·61 g cm^{-3}) comparable to those of box samples from the surface horizons of the Cottenham and Stackyard soils (1·59 and 1·62 g cm^{-3} respectively).

Archer and Smith (1972) found that maximum available water with tolerable air capacity is obtained in sandy loam with a bulk density of 1·50 g cm^{-3}, and in loamy sand of density 1·75. Hall *et al.* (1977) measured bulk densities ranging from 1·05 to 1·72 g cm^{-3} (mean 1·34) in sandy loams of the Wick series, and from 1·23 to 1·59 g cm^{-3} (mean 1·52) in loamy sands of the Newport series, both of which are considerably less than the optima given by Archer and Smith. The bulk densities of the sandy loams in upper parts of the Stackyard and Flitwick profiles range from 1·38 to 1·57 g cm^{-3} with a mean of 1·49, which is a fairly narrow range close to the optimum, but the loamy sands in upper parts of the Cottenham and lowest layer of the Stackyard profile have bulk densities ranging from 1·44 to 1·57 g cm^{-3} with a mean of 1·50, which is well below the optimum for maximum available water.

Total pore space, air capacity and available water. The undisturbed samples in each of the tins were wetted to near saturation, and then dried first on a sand suction table to 0·05 bar suction, then in a pressure membrane apparatus to 15 bar suction, and finally in an oven at 105°C. Water retained at 15 bar suction but released on oven-drying is regarded as not available to plants, whereas that released between 0·05 and 15 bar is water which will not drain under gravity but can be removed by the range of suctions exerted by plant roots (Hall *et al.*, 1977); it is termed available water (A_v). The remaining pore space consists of coarse pores, which drain under gravity and are occupied by air at a suction of 0·05 bar. It constitutes the air capacity (C_a), which is calculated by subtracting the volumes occupied by oven-dry soil, available and non-available water from the total volume of the sample. The volume of solid material, calculated from its weight and mean grain density (ranging from 2·64 to 2·70 g cm^{-3}), is divided into stones and fine earth (<2 mm). Fig. 7 shows the changes in volume percentages of all these soil components through the three profiles studied; intermediate values of moisture contents at −0·1, −0·4 and −2 bar potentials were calculated from regression equations given by Hall (unpublished), using the measured moisture contents at 0·05 bar suction, bulk density, and clay and silt contents.

In the Cottenham profile, total pore space ranges from 42% at 20–40 cm depth to 46% at 50–70 cm. Of this, 22–33% is air capacity, 7–14% available water and 5–9% non-available water. Comparison with values assembled by Hall *et al.* (1977, Fig. 21) places this profile in their 'moderate' class of soil structural quality; it has more than adequate air capacity, but the available water capacity is a limiting characteristic.

Total pore space in the Stackyard profile ranges from 40% in the topsoil and deep subsoil below 1 m to 48% at 0·5 m depth. Of this, 19–26% is air capacity, 10–16% available water and 5–10% non-available water, which again places the profile in the 'moderate' class of Hall *et al.* As with the Cottenham profile, the limiting characteristic is the small available water capacity, especially in the surface layer of the Stackyard profile. However, in the Cottenham profile available water decreases downwards to 7% at 70 cm, but in the Stackyard it increases downwards to 16% at 40 cm and only falls below 10% in a thin (5–10 cm) layer at about 1 m depth.

In the Flitwick profile, total pore space ranges from 35% at the surface to 46% at 50 cm depth, but excluding the slightly compressed topsoil gives a range of 42–46%. Of this, 14–18% is air capacity, 15–18% available water and 9–13% non-available water. Compression of the topsoil decreased its air capacity to 8%, and this loss is made up

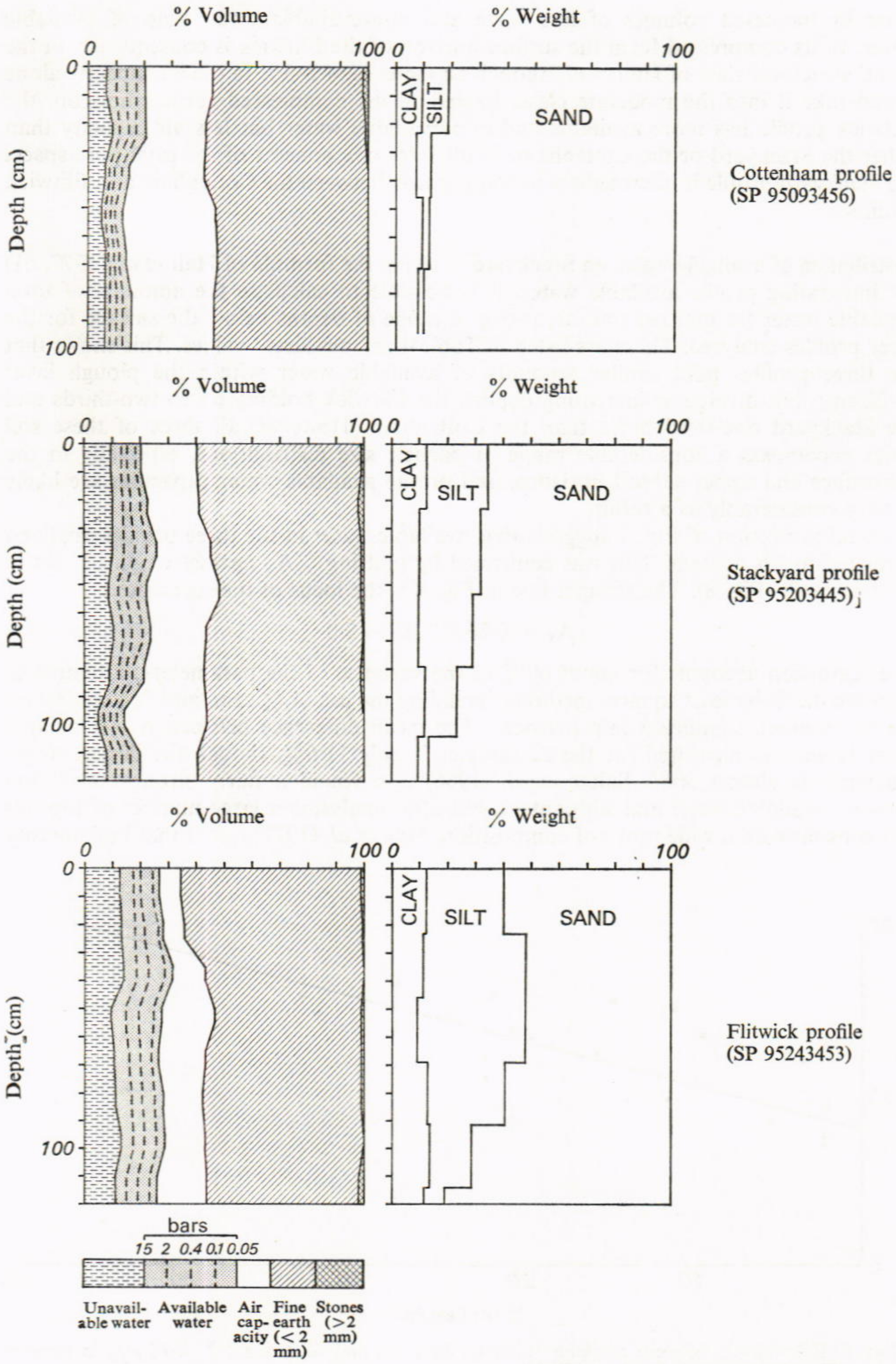

FIG. 7. Amounts of unavailable water, available water, air capacity, fine earth (<2 mm) and stones (>2 mm) as volume percentages, and clay (<2 μm), silt (2–63 μm) and sand (63–2000 μm) as weight percentages in profiles representing the Cottenham (C), Stackyard (S) and Flitwick (F) series on Stackyard Field.

more by increased volumes of fine earth and non-available water than of available water. In its compressed form the surface horizon of the Flitwick is consequently in the 'poor' structural class of Hall *et al.*, though an increase of 2–3% in the air capacity alone would take it into the moderate class. Excluding the compressed surface horizon, the Flitwick profile has more available and non-available water but less air capacity than either the Stackyard or the Cottenham. In all three components of the total pore space, the Stackyard profile is intermediate in composition between the Cottenham and Flitwick profiles.

Distribution of available water on Stackyard. Using the formula of Hall *et al.* (1977, 61) for integrating profile available water, it is possible to calculate the amounts of total available water (in mm per unit area) over a range of depths below the surface for the three profiles analysed. These are listed in Table 4 as 'measured' values. This shows that the three profiles hold similar amounts of available water within the plough layer (0–22 cm), but diverge at increasing depths, the Flitwick holding up to two-thirds and the Stackyard one-third more than the Cottenham. However, all three of these soil series encompass a considerable range of particle size distributions, especially in the subsurface and upper subsoil horizons, and profile available water capacities are likely to vary considerably as a result.

Visual inspection of Fig. 7 suggests that available water in the three profiles analysed is related to silt content. This was confirmed by plotting $\%A_v$ against weight % silt in the fine earth (Fig. 8). The straight line in Fig. 8 is the locus of the regression:

$$\%A_v = 0{\cdot}26 \times \%\,\text{silt} + 8{\cdot}0 \qquad (1)$$

The regression accounts for about 60% of the variance of the parameters; attempts to improve the fit by least squares methods, including the use of % sand and % clay values, did not make a significant improvement. The mean difference between A_v (calculated from 1) and A_v measured for the 22 samples is only 11·6%, though the largest single difference is almost 30%. Salter *et al.* (1966) also found a fairly strong correlation between available water and silt content, but after analysing a large number of topsoils and subsoils with a wide range of composition, Hall *et al.* (1977) found that bulk density

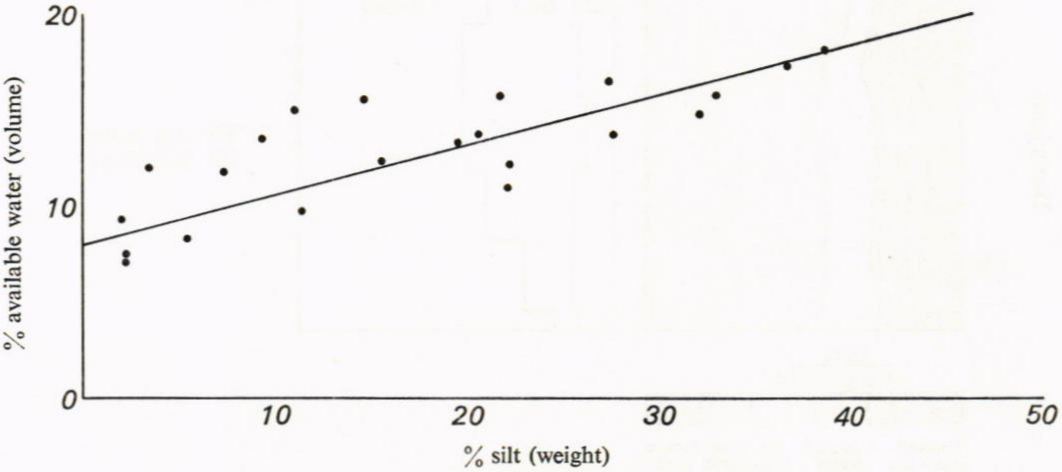

FIG. 8. Relationship between available water (volume %) and silt (weight % 2–63 μm) in samples from profiles C, S and F on Stackyard Field.

and organic C accounted for most of the variation in topsoil A_V, and bulk density and silt plus fine sand (2–100 μm) for most of the variation in subsoil A_V. It is therefore likely that the regression relationship (1) only holds for soils of sandy loam and loamy sand texture like those of Stackyard.

TABLE 4

Available water capacities (mm) of profiles representing the main soil types on Stackyard Field, Woburn Experimental Farm, from suction measurements on samples taken at points C, S and F (Fig. 1), and calculated from the silt contents of topsoil and subsurface samples at 10 m grid intersections surrounding these points

Profile	Depth (cm)	Calculated Max.	Min.	Mean	Measured	% Difference*
C. Cottenham profile (SP 95093456)	0–22	24	23	23	29	−21
	0–40	40	38	39	46	−15
	0–60	61	57	59	59	0
	0–80	81	76	79	78	+1
	0–100	101	95	99	97	+2
S. Stackyard profile (SP 95203445)	0–22	31	30	31	26	+19
	0–40	62	57	59	52	+13
	0–60	93	86	89	80	+11
	0–80	124	114	118	106	+11
	0–100	155	143	148	127	+17
F. Flitwick profile (SP 95243453)	0–22	35	34	34	22	+55
	0–40	67	60	63	61	+3
	0–60	101	95	95	97	−2
	0–80	134	120	126	128	−2
	0–100	168	150	158	161	+2

$$*\%\text{Difference} = \frac{\text{Mean calculated} - \text{Measured}}{\text{Measured}} \times 100$$

The suitability of equation (1) for predicting available water contents was further checked by calculating A_V values from the topsoil and subsurface silt percentages determined at the four or five 10 m grid intersections surrounding the three profiles C, S and F. Table 4 gives maxima, minima and means of calculated A_V for each of the three groups of grid points, and the percentage differences between the means and the measured A_V values of profiles C, S and F. A_V values calculated for the 0–80 and 0–100 cm depths are based on the assumption that the silt contents below 60 cm are the same as those determined in the subsurface (40–60 cm) layer. Measured and calculated values of A_V agree closely in the Cottenham and Flitwick profiles for all except the surface layer. The poor agreement for the topsoils probably reflects the importance of properties such as bulk density and organic content, which are largely independent of silt content, in determining topsoil A_V (Hall *et al.*, 1977). Agreement is also rather poor for all depths of the Stackyard profile, apparently because the silt contents of soils surrounding the profile are more variable than those surrounding profiles C and F, and are greater on average than those in profile S. Despite these discrepancies, it is clear that profile available water capacities on Stackyard can be predicted fairly accurately from silt percentages of the topsoil and subsurface layer. The technique at least has the merit of being quicker and cheaper than direct determination of available water capacity.

Fig. 9 shows the distribution of profile available water to a depth of 80 cm over the field. It is contoured from values at 10 m grid intersections for the sum of available water in the top 40 cm, calculated from topsoil (0–25 cm) silt contents using the regression in equation (1), and that at 40–80 cm depth similarly calculated from subsurface (40–60 cm) silt contents. Extrapolation to maximum rooting depths of 1·2 m or more using the

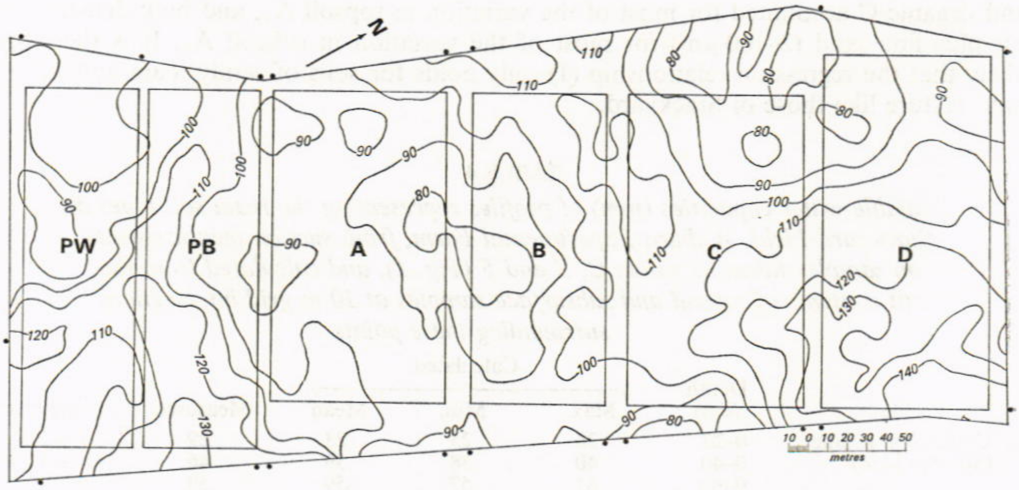

FIG. 9. Distribution of profile available water (mm) to 80 cm depth on Stackyard Field, based on surface (0–25 cm) and subsurface (40–60 cm) silt contents, and boundaries of main experimental sites (Permanent Wheat (PW), Permanent Barley (PB) and Series A, B, C and D).

values for silt contents at 40–60 cm depth would be progressively less reliable, as the transition from sandy loam or sandy clay loam to loamy sand or sand often occurs at or just below 80 cm in both the Stackyard and Flitwick series. This particular definition of profile available water is a compromise of both matric potential limits and depth of soil, largely determined by the analytical data available for the field. Crops such as cereals and sugar beet root deeper than 80 cm, but at such depths few can extract water to 15 bar suction. More complicated combinations of suction range and soil depth, such as those suggested by Hall *et al.* (1977, 66–68), could be presented for specific crops, but with less precision. The crop for which the values given in Fig. 9 are most applicable is potatoes.

The amounts of profile available water to 80 cm over the whole field range from 73 to 151 mm. Profiles corresponding to the Cottenham series contain 73–104 mm (mean 88·1), those corresponding to the Stackyard series contain 75–138 mm (mean 107·1), and those corresponding to Flitwick series contain 108–151 mm (mean 129·2). Of the three profiles in which available water was actually measured (C, S and F), the Stackyard with 106 mm to 80 cm depth and the Flitwick with 128 mm to 80 cm depth were therefore close to the mean for the respective series, but the Cottenham with only 78 mm to 80 cm depth was drier than average for the series, though probably not quite as dry as some soils on the western and southern sides of the knoll.

Droughtiness of the soil series. The average maximum potential soil moisture deficit for Woburn Farm is 160 mm (Hodgson, 1976, Appendix IV), so in terms of the soil droughtiness classes proposed by Hall *et al.* (1977, Table 11) for grassland (profile available water minus average maximum potential soil moisture deficit) the Cottenham series is everywhere very droughty (class d) and the Flitwick series is moderately droughty (class c), but the Stackyard series includes both very droughty and moderately droughty soils. To assess average drought risk for annual crops, allowances must be made for factors such as the absence of full ground cover (and therefore of full potential transpiration) early in the growing season, and the onset of senescence (the ripening period when further abstraction of soil moisture is not essential to the crop) before the date of maximum soil moisture deficit in late August or early September. Provisional models for cereals, potatoes and sugar beet are given by Hall *et al.* (1977, 62–68).

Crop growth in relation to water-supplying characteristics of the soils

Available water and limiting potential deficit. The limit of −15 bar potential for available water capacity is approximately equivalent to wilting point in most crops, but growth rates and final yields are limited for lack of water long before this point is reached. Penman (1971) defined the value of potential soil moisture deficit at which growth is retarded as the limiting potential deficit (D_l), and measured it for a range of arable crops in the irrigation experiment on Butt Close. In their discussion of the results of a similar irrigation experiment on Great Field, Rothamsted, French and Legg (1979) noted that the ratios of D_l for spring barley, main crop potatoes and field beans grown in the two experiments are similar to the ratio of profile available water (to 1·5 m depth) in Rothamsted and Woburn soils (Batcombe and Cottenham series respectively). The available water they quoted was that retained between −0·1 and −15 bar potentials, a slightly smaller range than our own measurements. However, recalculation of profile available water between these limits for profiles C, S and F (on Stackyard) extrapolated to 1·5 m depth (Table 5) shows that the Cottenham profile studied by French and Legg (from Road Piece, a field adjacent to the irrigation experiment on Butt Close) contained slightly more available water than profile C, and was consequently near the mean for Cottenham series on Stackyard field.

As the irrigation experiment on Butt Close was largely on soils of the Cottenham series, with only a small part near the north-east corner on Stackyard series (Catt *et al.*, 1975, Fig. 2), the D_l values quoted for Woburn are strictly only applicable to the Cottenham series. If we accept that the ratio of limiting potential deficit is the same as the ratio of profile available water, limiting potential deficits for the Stackyard and Flitwick series can be calculated from their profile available water contents (Table 5) and the limiting potential deficits derived from the Woburn and Rothamsted irrigation experiments. The calculated values (Table 6) are likely to be medians of fairly wide ranges,

TABLE 5

Profile available water capacities (mm) between −0·1 and −15 bar potentials for Rothamsted and Woburn soils (ratios Rothamsted/Woburn in brackets)

	Rothamsted	Woburn			
			Stackyard		
Depth (cm)	Great Field Batcombe series	Road Piece Cottenham series	Cottenham series	Stackyard series	Flitwick series
0–100	178	79 (2·3)	68 (2·6)	98 (1·8)	136 (1·3)
0–150	258	109 (2·4)	101 (2·6)	142 (1·8)	198 (1·3)

TABLE 6

Calculated limiting potential deficits (mm) for selected crops grown on the main soil series of Stackyard Field, Woburn Experimental Station

	Cottenham series	Stackyard series	Flitwick series
Spring-sown field beans	31	44	62
Main crop potatoes	32	47	65
Spring barley	38	56	77

especially for the Stackyard series, which probably overlaps ranges for the Cottenham series on the one hand and the Flitwick series on the other. Such predicted values clearly require confirmation by further irrigation experiments, but may be used provisionally to help interpret results from other experiments on the different soils of Stackyard.

Available water, rainfall and potato yields in the Six-course Rotation experiment. To demonstrate the significance of the variations in profile available water on Stackyard, we investigated briefly the relationship between available water and potato yields in the Six-course Rotation experiment run on Series B from 1930 to 1960. This crop was chosen out of the many for which there are yield data on Stackyard, because the depth to which we have estimated available water over the field (80 cm) is most applicable to a shallow-rooting crop such as potatoes, and earlier observations elsewhere on the farm (Catt *et al.*, 1977, 26) suggested that in some years potatoes show extreme yield differences in relation to the distribution of Cottenham and Stackyard series. Ideally yields should be discussed in relation to annual differences between limiting potential deficit and maximum potential deficit, or the length of time during the growing season when plots were at or below limiting potential deficit for the crop concerned. However, these data were not available to us for the whole period of the experiment. Instead, moisture stress during each growing season was estimated approximately from rainfall measurements for the period 1 May–1 September inclusive.

The results of the Six-course Rotation experiment were reported briefly by Yates and Patterson (1958), who explained that its main purpose (to measure the effects of weather and varying N, P and K rates on yields of six crops) was never fulfilled because of factors such as pest damage and 'fertility irregularities'. A strong response to N was obtained with potatoes, and this was significantly greater in years with high summer rainfall. However, no responses to P and K were obtained.

Preliminary examination of the results for potatoes showed that, irrespective of treatment, yields were often greater on plots along the northern side of Series B than on the southern side. The northern side is mainly on Stackyard series, profile available water ranging from approximately 93 to 124 mm (Fig. 9), and the southern side is mainly Cottenham series with rather less available water (75–108 mm approximately). Mean profile available water for each of the 90 plots was estimated from Fig. 9, and gave moderate correlations with yield ($r = 0{\cdot}40$–$0{\cdot}88$) for 12 of the 31 years, including those in which summer rainfall was the minimum (76 mm) and maximum (313 mm) for the period. However, the loci of regression were very variable, with some tendency for the plots with largest mean available water capacities to give small yields, especially in years with very wet summers (1931, 1936, 1954). The same tendency was also evident in other years, again those with moderate or large summer rainfall, when no correlation between yield and available water was found. Table 7 shows that in dry summers the greatest yields were obtained from plots with moderate or large available water contents, and as summer rainfall increased plots with progressively smaller available water tended to give the largest yields. Overall the largest mean yields were consequently obtained from plots with only moderate available water contents (95–99 mm).

To examine the pattern of yields in a way that is less affected by the possible occurrence of a bias due to treatments occurring in particular ranges of available water, the mean yields for each year and each treatment were subtracted from the individual yields, and the resulting residuals (after adding the mean yield over all years and treatments to give the residuals a zero mean value) were then averaged for ranges of available water and summer rainfall. The results (Table 8) confirm the conclusions already drawn from the direct comparison of yields, available water and summer rainfall, and emphasise the combined effects of either high available water and high rainfall or low available

TABLE 7

Effect of profile available water and summer rainfall (1 May–1 September incl.) on yields of potatoes (t ha^{-1}) in the Six-course Rotation experiment on Series B, Stackyard Field, 1930–60 (figures in brackets are the number of measurements from which each mean is calculated)*

Profile available water (mm)	Mean yield	Mean yields for years with summer rainfall (mm)			
		76–129	130–189	190–249	250–313
75–79	16·0	19·2	16·2	—	14·6
	(29)	(5)	(11)	(0)	(13)
80–84	17·9	19·7	18·7	21·4	15·9
	(30)	(5)	(11)	(2)	(12)
85–89	19·5	17·1	19·2	22·0	20·4
	(98)	(11)	(27)	(19)	(41)
90–94	20·0	19·1	19·9	—	18·7
	(53)	(8)	(23)	(0)	(22)
95–99	21·2	20·6	21·4	22·1	19·8
	(77)	(2)	(30)	(25)	(20)
100–104	19·2	20·3	17·6	21·3	19·1
	(99)	(19)	(33)	(19)	(28)
105–109	15·7	21·6	14·5	12·1	16·2
	(41)	(6)	(16)	(6)	(13)
110–114	16·0	20·7	14·3	10·4	17·7
	(38)	(4)	(14)	(4)	(16)

* Converted from original data in lb ac^{-1}

TABLE 8

Mean residuals of potato yields (t ha^{-1}) in the Six-course Rotation experiment (Series B, Stackyard Field, 1930–60) after removing the effects of treatments and year-to-year variations*

Profile available water (mm)	Summer rainfall (mm) 1 May–1 September	
	70–189	190–313
75–84	−1·9	−1·3
85–104	+0·6	+1·6
105–114	−2·7	−4·6

* Converted from original data in lb ac^{-1}

water and low rainfall in giving smaller yields than would be predicted from the effects of treatment and year to year variation.

The unexpectedly strong depression of potato yields in wet summers cannot be attributed to leaching of nutrients, as the response to N was greatest in the wet years. It is more likely to have resulted from pests or pathogens, such as nematodes, leaf fungi or bacterial stem infections, that could have been more active in wetter years and on the more moisture-retentive soils. For example, for free movement through the soil, nematodes require not only pores of adequate diameter (>30 μm approximately) but also water films several μm thick on the pore walls (Wallace, 1959), and these are more likely to have existed for long periods in the wetter years. They are also more likely to have persisted in the Stackyard series than the Cottenham, as it contains enough clay and silt mixed with the sand to provide abundant pores near the fine end of the drainable size class (approximately 60–200 μm diameter), which more easily retain the requisite moisture films between periods of rain. However, it should be emphasised that there is no direct evidence that any of these possible causes was largely or completely responsible for the small yields in the soils with most water.

Discussion and conclusions

Stackyard was originally added to Woburn Farm as the main experimental ground because other large fields, such as Warren Field, were found to have very variable soils. However, as early experimenters found, the soils of Stackyard are also non-uniform. Of the four series identified, one (the Husborne) occupies only a very small area delimited by a minor outlier of Chalky Boulder Clay near the southern boundary of the field. This outlier is the remnant of an originally continuous till sheet, which once covered the whole field, but was removed probably by periglacial erosion during the last (Devensian) cold period before about 8000 B.C. The glacial gravel deposited beneath the till was less completely eroded, and gives rise to stony phases (mainly of the Cottenham series) on some southern parts of the field and around the summit of the knoll near the north-west corner.

The three main soil series on the field (Cottenham, Stackyard and Flitwick) are delimited by means of particle size analyses of subsurface samples taken over a 10 m grid, and in the Flitwick series by the presence of mottling due to gleying within 70 cm of the surface. However, the textural difference between Cottenham series (<50% of the top 80 cm is sandy loam or heavier) and Stackyard and Flitwick (>50% sandy loam or heavier) is somewhat arbitrary, as there is a wide textural range on either side of this dividing line. Each of these three series is heterogeneous within certain limits, though the Cottenham is rather less heterogeneous than the other two.

Soil textural variability is strongest in subsurface horizons. The topsoil (0–25 cm) is much less heterogeneous, the minor changes that do occur in it across the field being related to those in the subsurface horizons. The deeper subsoil horizons are also comparatively homogeneous in particle size distribution, the sand or loamy sand of undisturbed Lower Greensand being encountered everywhere on the field at depths ranging from about 30 cm to almost 2 m. Most of the textural variation in both surface and subsurface horizons is due to changes in silt content; variation in clay content is much less, and clay and silt have dissimilar distributions across the field.

The distribution of Cottenham, Stackyard and Flitwick series is closely related to the surface topography of the field, the main features of which were probably inherited from the Devensian erosive phase. Cottenham series occurs on knolls and ridges, which are likely to have suffered minor subsequent (Flandrian) erosion following prehistoric deforestation and the commencement of agriculture. Stackyard and Flitwick series occupy the minor valleys, which are receiving sites for the Flandrian colluvium (soil eroded from higher areas). As the additional silt in these two soils is probably derived from Chalky Boulder Clay, much of the colluvium on Stackyard probably came from slightly higher ground covered by till to the east in what is now Woburn Park. The gleying in the Flitwick soils in lower parts of the valley near the north-east corner of the field was caused by annual rise of the water-table close to the surface during some past period, as the present water-table is too low to effect reduction and segregation of iron in the soil.

As the colluvium was probably deposited only in the last 3–4000 years, and is still accumulating on some parts of the field, the Stackyard and Flitwick soils developed in it are comparatively young profiles. Nevertheless, thin sections show evidence for moderate accumulations of illuvial clay in subsurface horizons of both series, though textural variation within the colluvium prevents both the profiles studied from being included in argillic subgroups. The relatively coarse texture of these soils has probably encouraged more rapid translocation of clay than is thought to have occurred over the same period in many other British soils. In the Bt2 horizon of the Stackyard profile, small patches of sand in which the grains are completely enveloped in illuvial clay provide some evidence of early Flandrian soil development prior to the deposition of colluvium. Together with a marked heterogeneity of almost all surface and subsurface horizons examined in thin section, these patches also indicate considerable macrofaunal disturbance of the soils to depths approaching 1 m, but as fresh colluvium has been added to many of the soils from time to time, the deeper faunal disturbance is as likely to be fossil as contemporary.

Excluding larger pores resulting mainly from macrofaunal activity ($>5\times10^6$ μm^2), which are difficult to measure precisely in thin section, the total volume of pores with areas >1250 μm^2 in the Stackyard profile is at a maximum of 8·1% in the Bt1 horizon, and decreases upwards to 4·4% in the topsoil and downwards to 3·3% in the 2Cu horizon. These are measures of the volume accessible to the soil mesofauna and larger members of the microfauna, though other soil and weather factors are likely to influence the occurrence of any particular group, such as nematodes (Jones & Thomasson, 1976). In soils containing roughly circular pores with few blind ends or marked constrictions, the water retained at field capacity, approximately $-0{\cdot}05$ bar matric potential (Hall *et al.*, 1977), is roughly equivalent to the total volume of pores with diameters <60 μm (i.e. approximate area 2800 μm^2). This size limit can just be reliably estimated from thin sections at the higher magnification we used, so the size distributions given in Fig. 2 are for only the finest of the pores that drain under gravity and are air-filled at field capacity. The total air capacity measured in another profile of the Stackyard series ranged from 19 to 26%, so the pores of area $<5\times10^6$ μm^2 form much less than half, and possibly as little as 15%, of the total volume of drainable pores.

Unless subjected to compaction by machinery or treading, the topsoil over most of the field is close to that providing the optimum combination of available water and air capacity. However, amounts of profile available water are much greater in the colluvial soils, especially the Flitwick series, than in the Cottenham series. Measured values of 161 mm for the Flitwick and 127 mm for the Stackyard (both to 1 m depth) are probably close to the means for the respective series, but the 97 mm measured in a Cottenham profile is probably less than average for the series on the field. Irrigation experiments at Woburn and Rothamsted suggest that the ratio of limiting potential deficits (the maximum soil moisture loss that can occur before crop growth is retarded) at the two sites is similar to the ratio of profile available water in the two soils, and on this basis different limiting potential deficits have been estimated for field beans, main crop potatoes and spring barley grown on the three main soil series of Stackyard. As yet it has not been possible to check these by relating them to experimental results for sites on the three soil types. However, potato yields in the Woburn Six-course Rotation experiment (on Series B of Stackyard) were re-examined in relation to profile available water to 80 cm depth, calculated from surface and subsurface silt contents using a regression established from the three profiles in which available water capacities were actually measured. This showed that, although yields were often considerably greater on the more moisture-retentive plots, the relationship was complicated by a strong depression of yields on some of the most water-retentive plots (Stackyard series), especially during years with high summer rainfall. This depression probably resulted from increased pest damage or disease on the more water-retentive soils in wet years.

The range of soil texture and moisture characteristics present even in such a small area of the field as Series B is therefore large enough to have major direct and indirect effects on yields, at least of potatoes. In view of this, further re-examination of results from the Six-course Rotation (for crops other than potatoes) and other experiments on Stackyard, using the distribution of profile available water given in Fig. 9, would seem to be justified. In addition, it is clear that this and other aspects of soil variability on Stackyard should be considered in the design of future experiments there.

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APPENDIX A

Profile descriptions

1 Cottenham (*stony phase*)

Location: Stackyard (SP 94953425)
Elevation: 97·0 m OD
Land use: rough grass at edge of experimental site

Ap,	0–22 cm	Very dark greyish brown (10 YR 3/2), slightly stony, sandy loam; medium to very small subangular quartzites and flints, angular carstone fragments; weakly developed medium subangular blocky structure, falling to crumb; friable; abundant fine fibrous roots; clear boundary.
Bw,	22–34 cm	Dark brown (7·5 YR 3/2), moderately stony, sandy loam; stones as above; very weakly developed medium subangular blocky structure, falling to crumb; very friable; many fine fibrous roots; clear boundary.
Cu,	34–70 cm	Brown (7·5 YR 4/4), very stony, loamy sand; many very small carstone and flint fragments, some larger platy carstones; loose; clear boundary.
2Cu,	70–87 cm	Yellowish brown, grey and reddish brown, colour-banded sand.

2 Stackyard series

Location: Stackyard (SP 94963428)
Elevation: 96·6 m OD
Land use: rough grass at edge of experimental site

Ap,	0–23 cm	Dark brown (7·5 YR 3/2), very slightly stony, sandy loam; medium to small subangular carstone fragments; moderately developed coarse subangular blocky structure, falling to crumb; friable; moderately plastic; common fine, fibrous roots decreasing with depth; clear boundary.
Bw,	23–42 cm	Dark reddish brown (5 YR 3/3), very slightly stony, sandy loam; medium to small quartzite, carstone and flint fragments; moderately developed medium subangular blocky structure; friable; moderately plastic; few fine fibrous roots; clear boundary.
Bt1,	42–72 cm	Dark brown (7·5 YR 3/2), very slightly stony, sandy loam; stones as above; moderately developed coarse subangular blocky structure; friable; moderately plastic; few fine fibrous roots; clear boundary.
Bt2,	72–91 cm	Very dark greyish brown (10 YR 3/2), very slightly stony, sandy loam, with many very fine, faint, clear, yellowish brown (10YR 5/8) mottles; small carstone fragments; moderately developed coarse subangular blocky structure; very friable; slightly plastic; clear boundary.
Bt3,	91–109 cm	Brown (7·5 YR 4/4) sandy loam; very weakly developed medium subangular blocky structure; very friable; clear boundary.
Bt4,	109–115 cm	Brown (7·5 YR 4/4), moderately stony, sandy loam; many platy

		carstone fragments, quartzite pebbles and flint chips; structure and consistence as above; clear boundary.
2Cu,	115–175 cm	Grey and brown, colour-banded sand.

3 Stackyard series

Location: Stackyard (SP 95023416)
Elevation: 100·0 m OD
Land use: rough grass at edge of experimental site

Ap,	0–19 cm	Dark brown (7·5 YR 3/2), very slightly stony, sandy loam; medium quartzite pebbles and carstone fragments, small and very small flint chips and carstone; weakly developed medium subangular blocky structure, falling to crumb; friable; slightly plastic; abundant fine fibrous roots, decreasing with depth; clear boundary.
Bw,	19–51 cm	Dark brown (10 YR 3/3), very slightly stony, sandy loam; stones as above; weakly developed coarse subangular blocky structure; friable; slightly plastic; common fine fibrous roots; clear boundary.
BC,	51–78 cm	Brown (7·5 YR 4/4), very slightly stony, sandy loam; stones as above; weakly developed medium subangular blocky structure; friable; slightly plastic; few fine fibrous roots; clear boundary.
Cu(g),	78–108 cm	Brown (7·5 YR 4/4), slightly stony, sandy loam, with many very fine, faint, yellowish brown (10 YR 5/8) mottles; stones as above; weakly developed medium subangular blocky structure; very friable; clear boundary.
2Cu1,	108–154 cm	Grey and yellowish brown, colour-banded, sandy loam; single grain; a grey (5 Y 6/1) clay seam at 130–131 cm; clear boundary.
2Cu2,	154–166 cm	Brown (7·5 YR 4/4) sandy clay loam; single grain; clear boundary.
2Cu3,	166–180 cm	Olive (5 Y 3/3) loamy sand, with a thin (5 mm) layer of yellowish red (5 YR 4/6) sand.

4 Stackyard series

Location: Stackyard (SP 95033447)
Elevation: 96·2 m OD
Land use: rough grass at edge of experimental site

Ap1,	0–7 cm	Dark greyish brown (10 YR 4/2) sandy loam; moderately developed fine granular structure; very friable; abundant fine fibrous roots; abrupt boundary.
Ap2,	7–17 cm	Dark brown (10 YR 4/3), very slightly stony, sandy loam; medium to small subangular flints and carstone fragments; moderately developed coarse subangular blocky structure, falling to crumb; friable; many fine fibrous roots; abrupt boundary.
Bw,	17–40 cm	Dark brown (10 YR 4/3), very slightly stony, sandy loam, with few fine, faint, diffuse, reddish brown (5 YR 4/3) mottles; medium to small subangular flints and carstone fragments, quartzite pebbles; structure and consistence as above; common fine fibrous roots; organic coatings to structure faces; abrupt boundary.
BC,	40–73 cm	Dark yellowish brown (10 YR 4/4), very slightly stony, sandy loam; stones and structure as above; friable to firm; common fine fibrous roots; abrupt boundary.

Cu,	73–92 cm	Brown (7·5 YR 5/2), very slightly stony, sandy loam; stones and structure as above; friable to loose; clear boundary.
Cu(g)1,	92–112 cm	Yellowish brown (10 YR 5/6) sand, with common fine, faint yellowish brown (10 YR 5/4) mottles; single grain; loose; clear boundary.
Cu(g)2,	112–115 cm	Brown (7·5 YR 4/4) sandy loam, with common fine, distinct yellowish red (5 YR 5/6) mottles; single grain; loose; clear boundary.
Cu(g)3,	115–129 cm	Light olive-brown (2·5 Y 5/4) loamy sand, with very many, medium to fine, distinct strong brown (7·5 YR 5/6) mottles; single grain; loose; clear boundary.
Cu(g)4,	129–134 cm	Strong brown (7·5 YR 5/6) sandy loam, with many medium to fine, distinct greyish brown (2·5 Y 5/2) mottles; single grain; loose; clear boundary.
2Cu1,	134–144 cm	Strong brown (7·5 YR 5/6) sand, with common medium, prominent greyish brown (2·5 Y 5/2) mottles; single grain; loose; clear boundary.
2Cu2,	144–180 cm	Light brownish grey (10 YR 6/2) sand, with common coarse, prominent yellowish red (5 YR 5/6) mottles; single grain; loose.

5 Flitwick series

Location: Stackyard (SP 95253458)
Elevation: 94·4 m OD
Land use: rough grass at edge of experimental site

Ap1,	0–7 cm	Dark brown (7·5 YR 3/2) sandy loam; moderately developed medium granular structure, falling to crumb; friable; slightly plastic; abundant fine fibrous roots; clear smooth boundary.
Ap2,	7–33 cm	Very dark greyish brown (10 YR 3/2) sandy loam; moderately developed coarse subangular blocky structure, falling to crumb; friable; moderately plastic; many fine fibrous roots; clear smooth boundary.
Bw1,	33–45 cm	Dark brown (10 YR 3/3), very slightly stony, sandy loam; medium to small subangular carstone and flint fragments; structure and consistence as above; common fine fibrous roots; clear boundary.
Bw2,	45–61 cm	Brown (10 YR 4/3), very slightly stony, sandy loam; stones and consistence as above; moderately developed coarse subangular blocky structure; clear boundary.
Bt(g)1,	61–69 cm	Brown (7·5 YR 5/4), moderately stony, sandy loam, with common fine, distinct yellowish red (5 YR 5/6) mottles; small friable subangular carstone fragments; moderately developed medium subangular blocky structure; very friable; moderately plastic; few fine fibrous roots; clear boundary.
Bt(g)2,	69–89 cm	Brown (7·5 YR 4/4), very slightly stony, sandy loam, with common fine, faint grey and ochreous mottling; small to very small flint and carstone fragments, and quartz pebbles; weakly developed coarse subangular blocky structure; very friable; slightly plastic; clear boundary.
2Cug1,	89–114 cm	Olive (5 Y 5/4) loamy sand, with very many, very fine, distinct strong brown (7·5 YR 5/6) mottles; single grain; loose: clear boundary.

2Cug2,	114–144 cm	Olive (5 Y 5/4) sand, with light olive-brown (2·5 Y 5/6, and dark yellowish-brown (10 YR 4/4) mottles; single grain; loose; a few traces; clear boundary.
2Cug3,	144–169 cm	Yellowish red (5 YR 5/6) loamy sand, with yellowish brown (10 YR 5/6) mottles; single grain; loose; clear boundary.
2Cug4,	169–177 cm	Dark grey (5 Y 4/1) loamy sand, with faint, diffuse brown and grey mottles.

6 Husborne series

Location: Stackyard (SP 94973415)
Elevation: 100·2 m OD
Land use: rough grass at edge of experimental site

Ap1,	0–12 cm	Dark brown (10 YR 3/3), slightly stony, sandy loam; small to very small subrounded and subangular quartzite and carstone fragments; massive structure, breaking to medium to coarse granular; moderately firm to firm; slightly sticky; moderately plastic; many fine fibrous roots; gradual boundary.
Ap2,	12–25 cm	Dark brown (10 YR 4/3), slightly stony, sandy loam, with a few very faint, fine diffuse brown mottles; stones as above, plus quartzite pebbles; moderately developed medium subangular blocky structure; consistence as above; common fine fibrous roots; clear boundary.
Btg,	25–39 cm	Dark brown (7·5 YR 3/6–5/6), slightly stony, sandy clay loam, with common very distinct, fine red (2·5 YR 4/6) mottles and some grey root channels; small subrounded flint and sandstone fragments; structure as above; moderately firm to firm; moderately sticky; very plastic; abrupt boundary.
2BCtg,	39–68 cm	Dark brown (10 YR 3/3), very slightly stony, slightly calcareous clay, with common very faint, fine strong brown (7·5 YR 5/8) mottles; very small rounded chalk and small subangular carstone and angular flint fragments; massive; very sticky; very plastic; few fine fibrous roots; clear boundary.
3Cg,	68–100 cm	Dark brown (7·5 YR 4/3), slightly stony, sandy clay loam, with very many, very fine, faint strong brown (7·5 YR 5/6) mottles; large to small subangular carstone and quartzite fragments; massive; moderately sticky, very plastic; few fine fibrous roots; clear boundary.
4C1,	100–122 cm	Strong brown (7·5 YR 5/6), loose, loamy sand; clear boundary.
4C2,	122–138 cm	Brown (7·5 YR 4/4), loose, gravelly, loamy sand; carstone fragments; clear boundary.
4C3,	138–180 cm	Light olive-brown (2·5 Y 5/4), loose, loamy sand, with light brownish grey (2·5 Y 4/6) and yellowish red (5 YR 4/6) mottles.

APPENDIX B

Micromorphology

2 Stackyard series

Ap, 0–23 cm (section at 10–18 cm): clay coatings, nodules and segregations absent; randomly distributed mineral grains are mainly quartz with a few well rounded flint or chert fragments, and a few variably weathered glauconite grains.

Bw, 23–42 cm (section at 30–38 cm): rare fine void clay coatings; nodules and segregations absent; strong evidence of turbation by fauna, probably mainly earthworms and enchytraeids, with common channels and chambers containing faecal pellets.

Bt1, 42–72 cm (section at 53–61 cm): common to many clay coatings to voids, and common fine, irregular and linear intrapedal clay concentrations, with a patch 2 mm across of sand grains coated and bridged by illuvial clay; few medium prominent ferruginous nodules; little variation in colour apart from a few distinct clear ferruginous segregations; common glauconite grains of all sizes up to about 600 μm across, variably shaped, weathered and coloured, and a few disintegrating; rare felspar grains.

Bt2, 72–91 cm (section at 79–87 cm): heterogeneous material, with 80% similar to that at 53–61 cm (poorly sorted sand grains in a largely silty s-matrix), 20% as irregular patches up to 15 mm across of sand grains coated and bridged by illuvial clay; common illuvial clay overall; a few small and medium, prominent ferruginous nodules; common prominent, distinct and faint, clear and diffuse ferruginous segregations; rare to few glauconite grains in silty material, but common, variably weathered and shaped in sandy pockets.

Bt4–2Cu boundary (section at 111–119 cm): upper 4 cm of well sorted sand grains coated and bridged by brown to dark brown clay, most of which is illuvial; lower 4 cm is uncoloured, well sorted single grain structure, with occasional fine clay coats and bridges; some clayey areas in the lower half may be weathered glauconite; variably weathered and coloured glauconite grains are common throughout, and some are disintegrating *in situ.*

5 Flitwick series

Ap2, 7–33 cm (section at 9–17 cm): clay coatings absent; few small and medium distinct ferruginous nodules; segregations absent; random distribution of particles; sand grains mainly quartz, with a few angular and subangular flint and quartzite fragments, rare charcoal fragments, and a few small weathered (orange and brown) glauconite grains.

Bw1, 33–45 cm (section at 34–42 cm): rare fine void clay coatings; nodules as above; many distinct and faint, diffuse and clear segregations, which are probably the result of fauna mixing this horizon with soil from the overlying Ap horizon; common medium and large (up to 6 mm across) earthworm and enchytraeid channels, often containing faecal pellets; an irregular patch 4 mm across of material similar to that of horizon below.

Bw2, 45–61 cm (section at 50–58 cm): few fine void clay coatings, often occurring in small patches; rare fine iron hydroxide coats to void walls; few medium and large prominent ferruginous nodules; common to many prominent and distinct ferruginous segregations; much faunal activity as above, with faecal pellets and darker Ap material incorporated into the matrix; s-matrix is silt-rich and often colourless; minerals as in Ap2 horizon.

Bt(g)2, 69–89 cm (section at 73–81 cm): common to many, irregularly distributed clay coatings to voids, and illuvial clay coating and bridging sand particles; few medium prominent ferruginous nodules; few prominent clear ferruginous and ferrimanganiferous and common distinct and faint, diffuse ferruginous segregations; patchy distribution of more clayey material, much of which may have been brought down to this level by fauna; remainder (50%) of material has a colourless, silty s-matrix; glauconite grains are variably weathered, some disintegrating and becoming amorphous.

6 Husborne series

Ap1, 0–12 cm (section at 3–11 cm): clay coatings absent; common small, medium and large, distinct ferruginous and ferrimanganiferous nodules; little variation in colour, apart from a few distinct, clear ferruginous and ferrimanganiferous segregations; mineral grains mainly quartz, with a few flint and quartzite fragments, and a few variably coloured and weathered glauconite grains; common faunal and root channels, often containing faecal pellets or undecomposed fibrous roots.

Ap2, 12–25 cm (section at 16–24 cm): similar to above; a few coarse sand particles are fragments of silty mudstone and ferruginous sandstone (carstone); rare well rounded quartz and flint stones 4–6 mm across.

Btg, 25–39 cm (section at 31–39 cm): common fine and medium void clay coatings, and few to common fine and medium, irregular and linear intrapedal clay concentrations formed by faunal turbation; some sandy pockets up to 15 mm across, where most of the clay bridging the grains is illuvial; larger mineral grains are sandstone and angular flint fragments; weathered glauconite grains are more common in the sandy pockets.

2BCtg, 39–68 cm (section at 52–60 cm): common to many fine to thick void clay coatings and common intrapedal clay concentrations; few small and medium, prominent ferruginous nodules; many prominent and faint, clear and diffuse ferruginous segregations.

4C1, 100–122 cm (section at 108–116 cm): moderately well sorted sand (mainly rounded quartz, with a few variably weathered glauconite grains) coated and bridged by many fine clay coatings; nodules and segregations absent.

4C3, 138–180 cm (section at 158–166 cm): predominantly single grain sand, mainly quartz and variably coloured, weathered and shaped glauconite grains, some of which are disintegrating and others have become amorphous; some local concentrations of clay are probably weathered glauconite grains, but a few may be illuvial.

Explanation of micromorphological terms

1 Clay coatings and intrapedal concentrations. Clay coatings (argillans) are concentrations of clay around voids, mineral grains or peds (natural soil aggregates). When viewed with a petrological microscope, they show strong optical continuity, strong preferred orientation, moderate birefringence, a sharp boundary with adjacent material and often a laminated appearance.

Intrapedal concentrations are similar microscopically to argillans, but have no relationship to voids or other free surfaces. They are believed to be clay coats, which have either totally infilled voids or have been disrupted and integrated into the matrix by soil faunal activity, shrinking and swelling movements or other soil-disturbing processes. When assessing the extent of clay illuviation (slow translocation down the profile by percolating water) for soil classification purposes, both clay coats and intrapedal concentrations are counted.

2 Other coats (cutans). These include concentrations of iron hydroxide or hydrated iron oxide (ferrans) around voids.

For coatings and intrapedal concentrations, the following scales of size and abundance are used:

size (μm thickness)	
very fine	<25
fine	25–150
medium	150–500
thick	>500

abundance (area %)	
rare	<0·2
few	0·2–2
common	2–4
many	4–10
very many	10–20
abundant	>20

3 Nodules and segregations. These are concentrations of oxides, hydroxides and hydrated oxides of iron and/or manganese as amorphous gels or crystalline forms, such as goethite, lepidocrocite, haematite or pyrolusite. Nodules have a regular, often circular shape, a sharp boundary to, and prominent or distinct contrast with, adjacent matrix material. Segregations are irregularly shaped and usually have a clear or diffuse boundary to, and prominent, distinct or faint contrast with, adjacent material. Iron and manganese are less evenly distributed in segregations than in nodules. Segregations correspond with the brown or red mottles recognised during macroscopic examination of the profiles.

For nodules and segregations, the following scales of size and abundance are used:

size (μm across)	
very small	<100
small	100–200
medium	200–2000
large	>2000

abundance (area %)	
few	0–2
common	2–20
many	20–40
very many	40–60
abundant	>60

Differences in contrast with the matrix material are defined as follows: (a) *faint*—indistinct segregations recognisable only on close examination, with little colour difference between them and the adjacent matrix; (b) *distinct*—segregations or nodules are readily seen, and are moderately different in colour from the adjacent matrix; (c) *prominent*—segregations or nodules are conspicuous due to strong differences in colour between them and the adjacent matrix.

Differences in sharpness of boundaries are defined as follows: (a) *sharp*—knife-edge boundaries between colours; (b) *clear*—colour transition <60 μm wide; (c) *diffuse*—colour transition >60 μm wide.