A STUDY OF PLANT/SOIL RELATIONSHIPS IN BARLEY GROWN IN SOIL CULTIVATED IN DIFFERENT WAYS

by

D.A.S. Lockhart, M.A., M.Sc.

A thesis submitted for the degree of
Doctor of Philosophy
University of Edinburgh
October 1971
## CONTENTS

### SUMMARY

### VOLUME I

#### SECTION

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Experimental - Methods and Materials</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Pretreatment period 1966-67</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>Shoot growth</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>4.1 Plant population</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>4.2 Stem population</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>4.3 Percentage of stems with ears at harvest</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>4.4 Mean stem mass at harvest</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>4.5 Shoot dry matter yield</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>4.6 Crop canopy height</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>4.7 Lodging</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>4.8 Shoot N, P and K content</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>4.9 Discussion</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>Grain yield</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>5.1 Grain yield</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>5.2 Grain dry matter percentage and maturity at harvest</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>5.3 Ear population</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>5.4 Number of grains per ear</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>5.5 1000 grain weight</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>5.6 Grain N, P and K content</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>5.7 Discussion</td>
<td>29</td>
</tr>
<tr>
<td>6</td>
<td>Measurement of root systems</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>6.1 Review of methods</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>6.2a Measurement of root length</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>6.2b Root length below depth of cultivation</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>6.3 Measurement of root diameter</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>6.4 Discussion</td>
<td>50</td>
</tr>
</tbody>
</table>
SECTION

7 Take-all incidence .......................... 73
   7.1 Review .................................. 73
   7.2 Experimental ............................ 78
   7.3 Discussion ............................... 81

8 Couchgrass incidence ......................... 86
   8.1 Review .................................. 86
   8.2 Experimental ............................ 88
   8.3 Discussion ............................... 90

9 General discussion ........................... 93

ACKNOWLEDGEMENTS

BIBLIOGRAPHY

APPENDIX

1 Field operations
2 Experimental operations
3 Meteorological information
4 Mean soil nutrient levels
4b Vertical distribution of pH, P and K in soil
5 Mean number of Lumbricus adults and immatures in plot samples on 19 September 1969

VOLUME II

FIGURE

1 Soil series
2 Top soil texture
3 Sub-soil texture
4 Soil drainage
FIGURE
5 Layout of experiment
6 Allocation of area within subplot for root sampling

PLATE
1 Field equipment
2 Dispersion of aggregates
3 Removal of fine soil fraction
4 Decanting roots off coarse fraction
5 Removal of water
6 Sample tray for root length count
7 Stereomicroscope arranged for root length count
8 Sample tray for root diameter count
9 Stereomicroscope arranged for root diameter count

TABLES
1 - 59 Botanical results
A - D Summary of soil results extracted from Soane's tables
SUMMARY

Four cultivation treatments (Deep, Shallow and Chisel ploughing and Direct drilling) were applied to the same plots each year at four rates of nitrogen application (0, 50, 100 and 150 kg N./ha).

The NIAE (Scottish Station) measured the effect of the cultivation treatments on soil bulk density, moisture content, air-filled porosity and mechanical impedance. Direct drilling increased bulk density and mechanical impedance, and reduced air-filled porosity.

The growth and development of spring barley in response to the treatments was measured. Plant establishment, although similar for all treatments in 1968 and 1969, was reduced by direct drilling in 1970. Direct drilling produced fewest tillers and ears each year. Although the deep ploughed treatment tillered more than the others, its final ear population was smaller than with shallow ploughing. Yield of grain was primarily determined by the number of ears per unit length of drill. If no nitrogen was applied, direct drilling reduced grain yield by 25%, whereas if 150 kg N./ha were applied, the yield without cultivation was similar to that of the tilled treatments.

Techniques were developed for the extraction and measurement of root systems. Root length was measured in three horizons (0-12, 12-24, 24-36 cm). Direct drilling restricted root growth in the top and middle
horizons, but had no effect in the lowest horizon. Deep ploughing increased root growth in the 24–36 cm horizon. Between 36 and 54 cm, tillage had no effect on root length. Root diameter was greater in the absence of cultivations. Although nitrogen increased root length, it did not affect root diameter.

Incidence of take-all increased rapidly on the shallow and chisel ploughed treatments, particularly in the absence of applied nitrogen. At high rates of applied nitrogen incidence of take-all was considerably reduced on all treatments.

Incidence of couchgrass was increased in the absence of tillage. Of the tilled treatments, control of couchgrass was best with deep ploughing.

Among the factors implicated in the reduction in grain yield on the direct drilled treatment were the reduced aeration and availability of soil nitrate and the increased mechanical strength of the soil. Subsidiary effects were attributed to the presence of take-all and couchgrass.
SECTION 1

INTRODUCTION

Background

Over the last two decades farmers in some areas have tended to change from rotational cropping towards intensive cereal growing. This change has resulted from improved broad-leaved weed control, the declining agricultural labour force, and the advantages of concentrating both capital and management resources on a single enterprise. The advent of the combine-harvester drastically reduced the labour requirement at harvest; while the heavy capital costs both of machinery and buildings encouraged cereal growers to make the best use of these assets by extending the number of years that cereals were grown in succession, and the average grown per annum.

Concentration on cereal growing soon revealed weaknesses in the abandonment of rotations. Grass weeds, particularly the couchgrasses and wild oats, soon became serious problems. The development of take-all and eyespot may seriously reduce cereal yields. Later, farmers discovered that the high yields of the first few years, and their system depended on high yields, were often followed by lower yields.

As introduction of the combine-harvester and its rapid spread, reduced the labour requirement at harvest, a smaller labour force found itself responsible for a
larger cereal acreage. The peak period of labour requirement moved to the drilling period; farmers found that, despite the heavier more powerful tractors available to them, more land was worked with fewer people in less suitable conditions. The impact of this system and its problems was recently revealed in the Agricultural Advisory Council Report (1970) on "Modern farming and the soil". A whole range of soils were found to be 'suffering' from the effects of the passage of heavy machinery over them in unsuitable conditions.

The Edinburgh experiment was designed as a result of the need to examine the requirement for cultivation and to discover if the limited number of suitable days could be better used if different cultivations were employed. The tillage systems selected included conventional ploughing at two depths, chisel ploughing and direct drilling (Jeater, 1966).

The effect of tillage on the physical state of the soil was measured by the Scottish Station of the National Institute of Agricultural Engineering (NIAE). Their results for 1968 and 1969 are presented in two unpublished reports by Soane, Campbell and Herkes (1970 & 1971). The soil results for 1970 will be included in a future report. The effect of tillage on the growth and development of a barley crop, together with the incidence of couchgrass and take-all, were measured. The response to increasing amounts of applied nitrogen and the interactions between tillage and applied nitrogen were also measured. During
the first three experimental years reported in this thesis, variates were selected for measurement and both sampling and measuring techniques were developed.
Site

In 1966 a four acre site was laid out in South Road field, part of Edinburgh University's Langhill Farm. The field is half a mile West of Roslin, between 500 and 550 feet above mean sea level.

The previous cropping was a three year ley from 1961 to 1964; in 1965 potatoes were grown. Since 1966, spring barley (Zephyr) has been grown each year. 1966 and 1967 were allowed for uniformity work. The soils of the area were comprehensively sampled by J.M. Ragg (Soil Survey of Scotland) for soil series (Fig. 1), top soil texture (Fig. 2), sub-soil texture (Fig. 3) and drainage (Fig. 4). Fixed markers were placed along the fence to ensure accurate siting of the trial on subsequent occasions. Five t/ha basic slag (13% citric soluble P₂O₅) were applied on 21 October 1966 and 750 kg/ha sulphate of potash (50% K₂O) on 3 December 1966. These were ploughed down to furrow depth of 25 cm.

Experimental layout

Figure 5 represents the plot layout. The eight replicates are divided into four main plots for tillage treatments and each main plot is divided into four sub-plots for nitrogen treatments.
Main plot treatments (T)  Sub-plot treatments (N)
Deep ploughing (D)  No applied nitrogen (N1)
Shallow ploughing (S)  50 kg N./ha (N2)
Chisel ploughing (C)  100 kg N./ha (N3)
Direct drilled (M)  150 kg N./ha (N4)

From autumn 1967 onwards the same treatments were applied to each plot every year.

Mainplot size inclusive of discard borders was 40 feet by 162 feet, subplots were 20 feet by 81 feet. Two adjacent corners of each mainplot were permanently marked with a one metre tube buried to a depth of 0.75 m. Each sub-plot was split into three areas (Fig. 6). The botanical sampling area was divided into 125 cells, 5 positions across its width and 25 along the length of the sub-plot. Sampling positions were predetermined each year for all types of sampling by random allocation. The NIAE used another area for their soil sampling; they operated a similar cellular system. The third and central area was reserved for grain yield measurements.

Field operations

Appendix I is a calendar of field operations coupled with a brief description. The ploughing treatments imposed each autumn were deep ploughing at 28-38 cm and shallow ploughing at 15-20 cm. Chisel ploughing was repeated three times during 1967-1968 and twice in the following years. The depth of chisel ploughing was the maximum achievable by the tractor in the prevailing soil
conditions: it varied between 15 and 36 cm. Paraquat (Gramoxone W) was sprayed on the stubble prior to direct drilling.

Soil analysis data is presented in Appendix 3a. In February 1970 ground limestone (850 kg/ha 45% CaO) was applied uniformly. Each year phosphate and potash were applied in February or early March (Appendix 1). Nitrogen in the form of Nitro-Chalk (21% N.) was applied by hand after drilling at the stipulated rates.

A triple disc Fernhurst drill was used for all plots; for direct drilling extra weights were fitted. A six foot combine-harvester, fitted with a special weighing hopper, was used for cutting the yield area.

Details of variates sampled in this experiment are given in Appendix 2; these include shoot and root measures, grain variates and the incidence of both take-all and couchgrass.
FIGURE A

TOP PART OF REPLICATE 1

1966

A B C D E F G H

101 102 103 104 105 106 107 108

1967
SECTION 3

PRETREATMENT PERIOD 1966-1967

The site for this trial was laid out in 1966, dressed with a compound fertiliser (74 kg/ha N., 34 kg/ha P$_2$O$_5$ and 34 kg/ha K$_2$O) in February 1966 and later drilled with barley. The plots were combine-harvested on 23 September 1966. On 16 March 1967 a compound fertiliser (75 kg/ha each of N., P$_2$O$_5$ and K$_2$O) was applied and followed by drilling on 27 March. The plots were combine-harvested on 4 September 1967.

Although in 1966 the trial occupied the same area as in subsequent years, each replicate was divided into 18 subplots, but subsequently changed to 16 plots. Yield assessment was based on the central 6 feet of each plot in both 1966 and 1967. In order to utilise the 1966 results, yields for that year were adjusted to correspond to the 1967 design. In Figure A (opposite) the first nine plots in 1966 are shown opposite the first eight plots in 1967; the two areas were identical. The areas used in 1966 for yield determination are hatched. Figure A demonstrates that 1966 plots A, B, C, G, H and I provided a reasonable assessment of the yield on plots now numbered 101, 102, 103, 106, 107 and 108. The yield for 104 was derived 2/3rds from D and 1/3rd from E, similarly the yield for 105 was derived 2/3rds from F and 1/3rd from E.

The grain yield data for 1966 and 1967 are presented
The results for these two years confirmed that differences were limited to replicates and seasons. Data were also collected for couch infestation based on the number of flowering heads in August 1967 and the vegetative incidence of couch in October 1967. There were considerable replicate differences for both these variates but no pre-treatment effects (Tables 58 & 59).
9.

SECTION 4

SHOOT GROWTH

Data were collected on plant and stem populations, the mean mass per stem, the proportion of stems with ears, the crop canopy height, degree of lodging and the N, P and K contents of the plant material. Dates of sampling and stages of growth varied between years, details of dates and sample sizes are given in Appendix 2.

4.1 Plant population (Table 1)

Soon after emergence (Feekes stage 1-2, Large, 1954) and on two subsequent occasions (Feekes stages 3-4 and 10-11) plant numbers were counted. Each year there was an apparent rise in population between May and June. As the purpose of sampling on the two later occasions was to establish the incidence of take-all, sample positions devoid of plants were disregarded, with the result that plant population was overestimated. These samples were dug up after tillering had started; when the samples were separated into plant units, groups of tillers may have been detached and counted as plants, thus further inflating the plant population.

There were no nitrogen effects, so only tillage treatment means are shown (Table 1). There were no tillage effects in 1968 or 1969. In 1970 direct drilling resulted in 5% fewer plants at emergence, 9% fewer in June and 12% fewer in July, indicating a
deleterious effect of direct drilling on plant survival.

4.2 Stem population (Tables 2-5)

On three occasions in 1968 and 1969, and four in 1970, stems were counted. Direct drilling tended to reduce stem population; in 1970 this reduction varied between 12 and 18%. Part of the 1970 reduction with direct drilling was due to a reduced plant population. There was no evidence that tillering was improved on the less dense direct drilled treatment. As only part of the reduced stem population was attributable to differences in plant stand, it is deduced that direct drilling also impeded tillering.

Effect of tillage on stem population at harvest, means as percentage of S

<table>
<thead>
<tr>
<th></th>
<th>1968</th>
<th>1969</th>
<th>1970</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep ploughing</td>
<td>100.0%</td>
<td>96.5%</td>
<td>95.2%</td>
<td>97.2%</td>
</tr>
<tr>
<td>Chisel ploughing</td>
<td>101.2%</td>
<td>94.2%</td>
<td>88.8%</td>
<td>94.7%</td>
</tr>
<tr>
<td>Direct drilling</td>
<td>94.2%</td>
<td>90.7%</td>
<td>83.2%</td>
<td>89.4%</td>
</tr>
</tbody>
</table>

At the June sampling date deep ploughing produced the most stems each year (3.7% more than the other tilled treatments). By harvest time shallow ploughing had an equal or greater stem population. Stem number reached a maximum during the growing season and then declined. The transition from most stems with deep ploughing to most stems with shallow ploughing occurred after maximum stem population because the latter treatment had the higher tiller survival rate.
Decline in stem population (maximum population - No. of ears) - mean of 3 years

- \( D = 47 \pm 2.00 \)
- \( S = 39 \)
- \( C = 40 \)
- \( M = 39 \)

Stem population responded to applied nitrogen. The response in June was linear with a quadratic component in 1968 and 1969. 150 kg N./ha increased the June stem population by 70% in 1968, 90% in 1969 but only 37% in 1970. Two weeks later the 1970 response was still linear but the increase due to 150 kg N./ha was 80%. The responses in late July and August were predominantly linear; the increases due to 150 kg N./ha were 88% in 1968, 58% in 1969 and 111% in 1970. At harvest the responses were linear in 1968 and 1970, but quadratic in 1969; the percentage increases due to 150 kg N./ha in 1968, 1969 and 1970 were 117%, 69% and 113% respectively. The small tillering response to applied N. in June 1970 followed a very dry period; later on tillering was profuse as July was wet. There was evidence of late second growth in 1968 too, as 150 kg N./ha increased stem population by 88% in June but 117% at harvest. In 1969, stem population reached an early maximum, possibly influenced by dry weather in July. A comparison of Tables 4 and 5 shows that the first nitrogen increment increased tiller survival between the two dates in 1968 and 1969 but further increments had no effect on survival: in 1970 applied nitrogen had no effect on percentage tiller survival between these dates.
Season had a considerable influence on the changes in stem population. In June the stem population at N1 was highest in 1970 and lowest in 1968. But as the nitrogen response was smallest in the former year and greatest in 1969, the mean population in June was greatest in 1969 and smallest in 1968. In 1970 nitrogen was applied as the crop reached full emergence, whereas in 1969 application was a fortnight before emergence. At harvest both the N1 population and the response were large in 1970 so its mean population was large too. In 1968 the N1 and N2 populations were small but as the nitrogen response was large overall, so its mean population was similar to the 1969 one.

4.3 Percentage of stems with ears at harvest (Table 6)

There was no tillage effect on the percentage of stems with ears at harvest. The highest percentage resulted from intermediate rates of applied nitrogen. Season also had little effect on the percentage.

4.4 Mean stem dry mass at harvest (Table 7)

Tillage had no effect on the mean stem mass at harvest, although tillage did affect stem density (Section 4.2). At very high densities, no increase in yield accompanies a further increase in population, because the density increase is offset by a reduced weight per stem. But if density is increased by a change in fertility, the growth of individual stems may
increase too, depending on the level of stem competition. As there was no evidence of an increase in stem weight on the lower density direct drilled treatment, it appeared that this treatment limited tiller growth.

The response to applied nitrogen was variable. In 1968 stem mass reached a maximum between N2 and N4, whereas in 1969 stem mass continued to respond to applied nitrogen at the N4 level. In 1970 there was no response to applied nitrogen. The N1 stem masses in 1969 and 1970 were identical and 15% heavier than in 1968, but at N4 the 1969 mass was 61% heavier than in 1970 and by this time half the shoot mass was in the ear.

4.5 **Shoot dry matter yield** (Tables 8-10)

Each June the yield of shoot dry matter (mean of N. rates) was lowest with direct drilling. At this stage of growth deep ploughing produced the largest yield each year. In July 1969 and 1970 the yield was still smallest with direct drilling but yield with shallow ploughing was larger than with deep ploughing. At harvest yield with direct drilling was still small, being 0.25, 0.52 and 0.54 t/ha less than the mean of the tilled treatments in 1968, 1969 and 1970 respectively.

<table>
<thead>
<tr>
<th>Effect of tillage on shoot yield at harvest, mean as % of S</th>
<th>1968</th>
<th>1969</th>
<th>1970</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep ploughing</td>
<td>94.2%</td>
<td>95.6%</td>
<td>98.5%</td>
<td>96.1%</td>
</tr>
<tr>
<td>Chisel ploughing</td>
<td>91.4%</td>
<td>92.3%</td>
<td>87.4%</td>
<td>90.4%</td>
</tr>
<tr>
<td>Direct drilling</td>
<td>92.6%</td>
<td>88.9%</td>
<td>88.0%</td>
<td>89.8%</td>
</tr>
</tbody>
</table>
14.

By harvest the yield with chisel ploughing was less than on the other tilled treatments.

Applied nitrogen increased yield at all rates on each sampling date; the response was quadratic with a large linear component. The responses in June at the N4 rate were 162%, 229% and 39% for 1968, 1969 and 1970 respectively. Both the nitrogen responses and the actual yields demonstrate the combined influence of sampling date and weather. In 1970 the yield in June was measured at growth stage 1-2 (Large, 1954), instead of growth stage 2-3 as in previous years. The small nitrogen response in June 1970 was partly the result of this early sampling. A contributory factor may have been the unusually dry weather (less than one inch of rain) between application of nitrogen in 1970 and the sampling date. In June 1968 yield was slightly heavier than in 1969 but the nitrogen response was less. The reduced nitrogen response in 1968 may have resulted from heavy leaching losses during May, as over 6 inches of rain fell during May 1968.

In July the shoot dry matter increases due to the application of 150 kg N./ha were 157% and 81% in 1969 and 1970 respectively. At harvest the responses were 138%, 162% and 106% for the three experimental years. Although mean shoot yields at harvest were similar in 1969 and 1970, the former year had the larger response to nitrogen and the latter year the larger yield at N1. The 1968 mean shoot yield was 20% lower than in the other two years; its yield at N1 was the lowest and nitrogen response was mediocre.
4.6 *Crop canopy height* (Tables 11-12)

Direct drilling produced the shortest crop in June (5.5%), thereafter tillage had little effect on height. In 1970 there was no evidence that tillage reduced crop canopy height.

Applied nitrogen increased crop height; the response was highest in 1969 and lowest in 1970. Direct drilling and chisel ploughing had a larger linear component in their 1970 nitrogen response than the other two ploughed treatments.

4.7 *Lodging* (Tables 13-16)

The lodging figure was the proportion of the crop on the yield area (Fig. 6) that was not standing vertically. Severe lodging was the proportion laid almost horizontally. Tillage had no effect on lodging at growth stage 10.5 to 11.2 (Large, 1954) (Table 13). By growth stage 11.3 in 1970 there was slightly more lodging on the deep ploughed treatment than on the other treatments.

Lodging increased rapidly at the higher rates of applied nitrogen. At harvest 1970 severe lodging was worse than in previous years, but as it resulted from a series of heavy thunderstorms shortly before harvest it had little effect on grain development. In 1968 the increase in lodging at the higher nitrogen rate was particularly large.
4.8 Shoot N, P and K content

Nitrogen (Tables 17-21)

On 24/28 June 1968 the nitrogen percentage in the shoot dry matter was highest in the direct drilled treatment. In 1969 (17/19 June) the percentage was high with deep ploughing and direct drilling. On 1/2 June 1970 deep ploughing had the highest percentage N. in the shoot dry matter, but by harvest all tillage treatments were similar.

The yield of nitrogen in the shoots in June was greatest with deep ploughing as it combined a large percentage of N. with a large yield. In 1968 and 1969 the yield of nitrogen with direct drilling was similar to that with shallow and chisel ploughing because its smaller dry matter yield was balanced by its increased nitrogen percentage. In 1970 both dry matter yield and percentage nitrogen were small for the direct drilled treatment, consequently its yield of nitrogen was small too.

Applied nitrogen increased both the percentage of nitrogen in the shoots and the total shoot yield of nitrogen on all sampling occasions. Compared with 1968 the June shoot yield was less in 1969, but its yield of nitrogen was the greater, thus demonstrating that more nitrogen was available to the crop in 1969.

Phosphate (Tables 21 & 22)

Tillage had no effect on the percentage phosphate in the shoots in June 1969, but in June 1970 this percentage was highest with deep ploughing and lowest with direct
drilling. By harvest the percentage was highest with direct drilling and lowest with shallow ploughing. The phosphate percentage is dependent on the rate of uptake by the crop and the rate at which labile phosphate is replenished from the soil reserves. Differences between treatments depend on changes in growth altering the balance between demand for phosphate by the crop and the accessibility of the roots to labile phosphate. If the sink increases at a rate faster than the labile phosphate replenishment rate then the concentration of phosphate in the shoots declines. In June 1970 the differences in sink size were small (0.11 t/ha) compared with 1969 (0.54 t/ha), so it appeared that deep ploughing increased crop accessibility to phosphate to a greater extent than sink size. As both sink size and percentage phosphate in shoots were reduced in the absence of tillage, it appeared that direct drilling limited accessibility of the roots to phosphate.

Although there was a tendency for applied nitrogen to reduce the percentage of phosphate in the shoot, actual uptake increased. It appeared that the increase in sink size exceeded the rate of phosphate replenishment from soil reserves.

Potash (Tables 23 & 24)

In June the potash percentage tended to be highest on the deep ploughed treatment and lowest on the direct drilled treatment. Sink size was largest with deep ploughing in both years, consequently this treatment
increased the accessibility of potash to the roots. As percentage of potash in the shoots tended to increase when nitrogen was applied, it appeared that potash was more accessible on the higher yielding treatments. On 1/2 June 1970 45% of the final potash yield was in the shoots, consequently potash uptake was rapid early in the growing season. By harvest there were no differences in the potash percentage in the shoots.

4.9 Discussion

Wellings (1968) reviewed the results of direct drilling on five Experimental Husbandry Farms. Mechanical problems associated with drilling, together with slug damage, caused several crop failures. Jeater and Laurie (1966) and Jeater (1966) both found that crop establishment was reduced by direct drilling, particularly on heavy soils. On the South Road trial an improved purpose-built drill was used. In 1968 and 1969 the performance of this drill, in terms of plant establishment, was similar for all tillage treatments. In 1970 the reduction in plant stand at emergence on the direct drilled treatment was due to the low establishment on mainplot 31. According to Finney and McIlvenny's guide lines for direct drilling (1970) this mainplot was in the replicate least suited to direct drilling, its drainage was imperfect, its soil texture relatively heavy and it had a large couchgrass infestation. If a missing value was calculated for mainplot 31 and used in the analysis of variance most of
the variation was eliminated. Plant population was also small on the direct drilled treatment in June and August 1970, even if mainplot 31 was disregarded. This was evidence that direct drilling reduced the ability of soil to support large plant populations.

Kirkby (1967) found that tillering increased at low seed rates. There was no evidence of compensatory tillering on the direct drilled treatment even though its plant stand was less dense. Tillering on this treatment was low in comparison with the others; the stem population was reduced by 15% whereas the plant population reduction at emergence was only 5%. Covariance was used to adjust the plant population in 1970 to a common stand; it reduced a significant proportion of the variation in stem population, but the remaining differences were still significant. Although this use of covariance is controversial (Cochrane & Cox, 1957; Smith, 1967), it did demonstrate that stem population differences were not solely due to differences in initial plant population and that after braiding crop development was affected by tillage.

In most seasons tiller number reaches a maximum and then declines until ear emergence (Kirkby, 1967). However, if wet conditions coincide with the later stages of vegetative development tiller production may be resumed. As stem population with direct drilling was still smallest after the period of declining stem population, it appeared that direct drilling changes the
environment's capacity to support ears.

Comparison of yield and stem population (Tables 2 & 8) shows that in 1968 and 1969 (data for 1970 was not comparable) yield differences between deep and shallow ploughing were solely due to their different stem populations. Bremner (1969a) has shown that stems compete for survival and that the early ones survive better than later ones. However, extensive tillering can be deleterious to yield if accompanied by a reduced shoot survival rate (Bingham, 1967). Bremner (1969a) found that early application of nitrogen tended to promote tillering rather than stem growth. With deep ploughing there was evidence of profuse tillering early in the season being followed by a reduction in shoot survival rate; this effect was similar to that experienced by Bremner with early nitrogen. Bremner found that late application of nitrogen increased tiller survival but had no effect on the maximum number of tillers produced. As the difference between tiller populations for the deep and shallow ploughed treatments was small, it would appear that early in the season soil conditions with deep ploughing promote faster growth than those with shallow ploughing: this effect was temporary, hence the differences in the tiller survival rates for these two treatments determined the stem population at harvest.

Variation in the shoot yield among treatments was caused by differences in the stem population and to a lesser extent by stem mass differences. As the stem
masses at harvest were similar for all tillage treatments there was no evidence of stem growth compensating for density differences; consequently the factors that reduced density relative to the shallow ploughed treatment also limited stem growth.

Between seasons, mean stem population and mean stem mass varied considerably (by up to 29 and 27% respectively). Both variates were subject to the influence of weather, and so too were the nitrogen responses. In the absence of applied nitrogen there were seasonal effects such that in 1970 the stem population was greatest at harvest and in 1968 the mean stem mass at harvest was smaller than in the following two years. Stem population is increased by applied nitrogen, so also is the mean stem mass at low population pressures. In late June 1970 the stem population was higher than in the previous two years. By harvest, yield at N1 was heaviest in 1970. As mean shoot masses at N1 were similar at harvest in 1969 and 1970, the increased yield in the absence of nitrogen in 1970 resulted from its larger stem population; this was probably induced by a combination of nitrogen taken up in the early stages of growth and wet conditions in the later stages of vegetative growth (Kirkby, 1967).

Stem population response to applied nitrogen varied considerably between years, so also did the stem population in the absence of applied nitrogen. Cereal growth follows a succession of stages (Large, 1954), although this succession is complicated by late-developing tillers
(Cannell, 1969); the period of maximum tiller production (Kirkby, 1967) precedes the period of maximum dry matter yield. Nitrogen stimulates both tillering and stem growth. In 1969 the tillering response to applied nitrogen was relatively early, thereafter nitrogen tended to increase stem mass. In 1968 and 1970 tillering was profuse during the later stages of vegetative growth so that mean stem mass response to applied nitrogen was parabolic in 1968 and tended to be negative in 1970.

As tillage had little effect on the N, P, and K percentages at harvest, yield of these nutrients was proportional to dry matter yield. Earlier in the year substantial differences, both in sink size and percentage of nutrients in the shoots, indicated that differences in nutrient availability, or crop accessibility to the nutrients, existed. During the main tillering period both nutrient yield and percentage were large with deep ploughing; this indicated that the soil environment was conducive to early growth and that nutrient availability was increased by this treatment. But this increased nutrient availability was transitory as by harvest nutrient yields for deep and shallow ploughing were the same. In June 1970 direct drilling reduced both the percentage of nutrients in the shoots and also the shoot yield. A reduction in both variates is indicative of reduced nutrient availability and a restriction on crop growth. In 1968 and 1969 direct drilling did not reduce nutrient percentage, consequently differential nutrient
availability was a temporary characteristic of this treatment, but the effect of restricted growth was permanent.
SECTION 5

GRAIN YIELD

Data were collected on grain yield, its dry matter percentage, ripeness at harvest, 1000 grain weight and the N, P and K content of the grain. The ear population was counted and the number of grains per ear calculated. Yield was measured on a six foot strip diagonally inclined across the yield area (Fig. 6). The grain variates were measured on sub-samples.

5.1 Grain yield (Tables 25-27)

Yield varied considerably between seasons (Table 25). As 1966 and 1967 were pretreatment years, yields for these years (Table 26) are not comparable with yields in the three experimental years. The yield of replicates varied in that replicate II was highest yielder in 1967, but lowest in 1970; replicate VIII was lowest in 1968 but second highest in 1970. Yields were consistently large on replicate IV and consistently small on replicate VII. During 1966-1969 the East bank of plots yielded more grain than the West bank.

Each year grain yields (Table 27) were largest with shallow ploughing and smallest with direct drilling. Yield with deep ploughing was consistently larger than with chisel ploughing.
Effect of tillage on grain yield, mean as percentage of shallow ploughing

<table>
<thead>
<tr>
<th></th>
<th>1968</th>
<th>1969</th>
<th>1970</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep ploughing</td>
<td>99.3</td>
<td>97.6</td>
<td>92.7</td>
<td>96.5</td>
</tr>
<tr>
<td>Chisel ploughing</td>
<td>97.3</td>
<td>94.9</td>
<td>91.2</td>
<td>94.4</td>
</tr>
<tr>
<td>Direct drilling</td>
<td>89.4</td>
<td>89.4</td>
<td>87.2</td>
<td>88.7</td>
</tr>
</tbody>
</table>

The relative yield with shallow ploughing tended to increase from 1968 to 1970. The yield with direct drilling increased relative to the yields with deep and chisel ploughing.

The yield response to applied nitrogen was quadratic; in 1968 yield of grain increased by 1280 kg/ha in response to the first 50 kg N./ha, whereas the grain increase resulting from the third 50 kg N./ha increment was only 100 kg/ha. In 1968 and 1970 the mean increase in grain yield for each kg N./ha applied at the N4 rate was 13.5 kg/ha compared with 17.3 kg/ha in 1969. Yields of grain at N1 were almost the same in 1969 and 1970, but in the former year yield response to applied nitrogen was the greater. Although grain yield responses to applied nitrogen were similar in 1968 and 1970, the 1970 yield at N1 was 63% greater than in 1968.

Compared with the tilled treatments the yields with direct drilling were 21% less at N1 but 1% heavier at N4.

5.2 Grain dry matter percentage and ripeness at harvest (Tables 28 & 29)

Chisel ploughing tended to produce an early ripening
crop, consequently its dry matter content was high. There were no other tillage differences.

Both grain dry matter percentage and maturity responded in a similar manner to applied nitrogen. In 1968 and 1969 the lowest dry matter was on the N1 treatment. In 1970 the highest dry matter and most mature grain was on the N1 treatment. Nitrogen encouraged late tillering in 1970; many of these tillers were green at harvest and so depressed dry matter percentage. The dry matter percentage with direct drilling at N1 was low compared with the tilled treatments; at N4 there were no differences.

5.3 Ear population (Table 30)

Direct drilling produced the least number of ears each year, and shallow ploughing produced the most. In 1968 and 1969 there were no differences between deep and chisel ploughing, whereas in 1970 deep ploughing produced 7% more ears.

Effect of tillage on ear population, mean as a percentage of shallow ploughing

<table>
<thead>
<tr>
<th></th>
<th>1968</th>
<th>1969</th>
<th>1970</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep ploughing</td>
<td>95.6</td>
<td>96.5</td>
<td>94.4</td>
<td>95.5</td>
</tr>
<tr>
<td>Chisel ploughing</td>
<td>96.9</td>
<td>95.2</td>
<td>88.1</td>
<td>93.4</td>
</tr>
<tr>
<td>Direct drilling</td>
<td>92.4</td>
<td>90.4</td>
<td>80.3</td>
<td>87.8</td>
</tr>
</tbody>
</table>

Ear populations on the chisel ploughed and direct drilled treatments were small in 1970. During the experimental period the performance of treatments declined
relative to shallow ploughing; this was most evident on the direct drilled and chisel ploughed treatments.

Applied nitrogen increased ear production; in 1968 this effect was virtually linear whereas in the other two years there was a clear quadratic component also. The ear populations at N1 in 1968 and 1969 were similar and 21% less than in 1970; at N4 the 1968 and 1969 populations were less than in 1970 by 23 and 33% respectively. Ear population was small in 1969 due to the small effect of nitrogen on a small population, compared with a large effect on the large population in 1970. In 1968, population was small but the effect of applied nitrogen was large.

5.4 Number of grains per ear (Table 31)

Tillage had no effect on the number of grains per ear. The effect of nitrogen on this parameter varied between years. In 1968 the response reached a maximum between N1 and N3, in 1969 the response was positive and in 1970 the response appeared to be negative. At N4 in 1969 there were 24% more grains per ear than in 1968 and 39% more than in 1970, compared with only 12 and 9% respectively at N1. The mean in 1969 was 12% and 26% larger than in 1968 and 1970 respectively.

5.5 1000 grain weight (Table 32)

Tillage had no effect on 1000 grain weight in 1968 and 1970. In 1969 1000 grain weight was heaviest on shallow ploughed and direct drilled treatments. Despite
the increased grain production per unit area, shallow ploughing did not reduce grain size.

Effect of tillage on 1000 grain weight mean as percentage of shallow ploughing

<table>
<thead>
<tr>
<th></th>
<th>1968</th>
<th>1969</th>
<th>1970</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep ploughing</td>
<td>98.2</td>
<td>98.3</td>
<td>96.8</td>
<td>97.8</td>
</tr>
<tr>
<td>Chisel ploughing</td>
<td>98.8</td>
<td>97.9</td>
<td>98.4</td>
<td>98.4</td>
</tr>
<tr>
<td>Direct drilling</td>
<td>97.0</td>
<td>100.2</td>
<td>99.7</td>
<td>99.0</td>
</tr>
</tbody>
</table>

These differences were small in comparison with grain yield differences.

Nitrogen responses varied between years: in 1968 a maximum was reached between N1 and N3, in 1969 the response was positive and in 1970 there was no clear response. In 1969 the 1000 grain weight for direct drilling at N1 was low relative to the tilled treatments, at N4 it was much heavier. The overall positive response to applied nitrogen in 1969 was due to the large N4 figure for direct drilling disguising small negative responses at N4 on the tilled treatments. Maximum response to applied nitrogen occurred at a higher rate on the untitled treatment.

The mean 1000 grain weight in 1969 was 27% and 12% heavier than in 1968 and 1970 respectively.

5.6 Grain N, P and K content (Tables 33-38)

As the percentage of nitrogen in the grain was not affected by tillage treatments, differences in yield of nitrogen in the grain (Table 34) were due to the effect of tillage on grain yield. Although applied nitrogen
increased the overall percentage each year, in 1968 and 1969 increase in yield was so large at the N2 rate that it resulted in dilution of nitrogen in the grain.

The nitrogen percentage in the grain was largest in 1970 and smallest in 1969. Applied nitrogen increased the percentage of nitrogen in the grain most in 1970 (23%) and least in 1968 (11%). Yields of nitrogen in the grain were similar for 1969 and 1970 as the larger grain yield response in 1969 was balanced by the percentage nitrogen in the grain being larger in 1970.

Tillage treatments had no effect on the percentage of P or K in the grain. Nitrogen had no effect on the percentage of P, but it reduced the percentage of K. The dilution effect for K was only 5% compared with a 95% increase in actual uptake.

5.7 Discussion

Grain yield is the product of weight per grain, number of grains per ear and number of ears per unit area. Grain size is controlled genetically (Willey & Dent, 1969; Holliday & Willey, 1969), but both population density and fertility also affect grain size. If fertility remains constant, grain size is reduced by factors that increase population density. If nitrogen is used to vary the fertility, the grain size response is parabolic, and dependent on the interaction between the effects of greater nitrogen availability and the increased demand for nitrogen due to the dense stem population. Grain size is
also influenced by the presence of other grains (Bingham, 1969); emasculation of wheat ears (Cappelle) to produce different grain numbers resulted in an increase in grain size if grain number was reduced.

In 1968 and 1969 on the South Road trial stem populations at harvest were similar, but grain size was smaller in 1968. The grain size in 1969 was also larger than in 1970. Mildew was widespread in 1968 and to a lesser extent in 1970; this fungus reduces the area of leaf capable of photosynthesis. Lack of bright sunshine in the period following ear emergence may also severely limit grain development. The duration of bright sunshine in July was 104.8, 179.6 and 105.2 hours for 1968, 1969 and 1970 respectively. A combination of less sunshine and more mildew probably reduced grain size in both 1968 and 1970. The grain size in 1970 at high rates of applied nitrogen was further reduced by the large increase in population density.

Although direct drilling and shallow ploughing tended to produce heavier grains, there were no differences between tillage treatments in the yield of grain per ear. Differences in weight per grain and grains per ear were small for tillage treatments and were generally inversely related, consequently the number of ears produced per unit area was the yield component most affecting grain yield. As there were no differences in the percentage of stems producing ears, attributable to tillage, ear number per unit area was directly related to tiller production and
survival. There were small deviations from this relationship: in 1968 the deep ploughing grain yield was large relative to its ear production because its ears contained 3% more grains. In 1970 the yield with shallow ploughing was small relative to its ear population due to a 6% reduction in the number of grains per ear.

A shading experiment on barley (Holliday & Willey, 1969) demonstrated that shading from establishment to ear initiation reduced yield. There were reductions in tiller survival and ultimately in the number of ears per unit area. Kirkby (1967) has shown that the number of ears per unit area tends to be fixed earlier in the growing season than spikelet number or grain size. If restriction on light early in the season limited potential ear production, possibly soil factors operating during this period may also limit potential ear production. Tillage in the South Road trial affected soil physical conditions (Tables A, B, C & D) and stem populations. Holliday (1960) reviewed work on plant populations and demonstrated that grain yield decreased at large plant densities. Bingham (1967) found that prolific tillering could be accompanied by reduced survival and production of ear, with the result that grain yield was reduced too. Although deep ploughing produced most stems, its proportion surviving to harvest was the lowest, whereas shallow ploughing produced slightly fewer stems but a higher proportion of them survived to support ears. As there were no differences in the weight of grain per ear for
tillage treatments, shallow ploughing resulted in the largest grain yields.

As the weight per grain response to applied nitrogen was parabolic in 1968 and 1970, the demand for nitrogen at the high stem densities exceeded the extra nitrogen supplied. The positive grain size response to applied nitrogen in 1969 indicated that either the population pressure was less in that year, or else the environment was capable of supporting a larger crop. As ear emergence in 1969 was followed by more bright sunshine than in the other years, and the lowest incidence of mildew, environmental conditions appeared to suit grain development even at high stem densities. The grains per ear responses to nitrogen were similar to those described above in connection with grain size.

A comparison of the influence of nitrogen on yield and its components is shown below.

**Effect of N. on grain yield and its components, means as percentage of N1**

<table>
<thead>
<tr>
<th></th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>160%</td>
<td>190%</td>
<td>205%</td>
</tr>
<tr>
<td>Weight per grain</td>
<td>104%</td>
<td>103%</td>
<td>102%</td>
</tr>
<tr>
<td>Grains per ear</td>
<td>106%</td>
<td>106%</td>
<td>104%</td>
</tr>
<tr>
<td>Ear number per unit area</td>
<td>148%</td>
<td>177%</td>
<td>200%</td>
</tr>
</tbody>
</table>

Although weight per grain and grain number per ear modified the grain response to nitrogen, the major factor affecting grain yield was ear population. The tendency for tillage to result in yield and ear population
differences at the lower rates of applied nitrogen but not at the higher rates was similar to van Dobben's results with seed rates and yield (1966). Van Dobben found that at low rates of applied nitrogen grain yield could be increased by an increase in seed rate, but at high rates of applied nitrogen grain yield was less responsive to seed rate. Both the grain yield and ear population responses between N1 and N3 were least with deep ploughing. Between N3 and N4 the response with direct drilling for both ear population and yield was greater than that with the tilled treatments. Furthermore, the reduction both in grains per ear and weight per grain between N3 and N4 was least on the direct drilled treatment. The combination of ear population, grains per ear and weight per grain responses to applied nitrogen resulted in there being no differences between direct drilling and the tilled treatments at the higher nitrogen rates.

The profitability of applying nitrogen to cereals depends on the increase in grain yield resulting from the extra nitrogen. As nitrogen costs about four times the selling price of grain, a return in excess of four parts cereal per part of applied nitrogen is required to cover the extra cost of the applied nitrogen. The grain yield return between N2 and N3 on the tilled plots was 11.2 kg/ha of grain per kg N./ha applied. Between N3 and N4 the return was 5.1:1. The returns with direct drilling were 17.4:1 and 10.2:1 for the N2-N3 and N3-N4 increments respectively. Optimum output was achieved at a higher nitrogen level on the untilled treatment.
THE MEASUREMENT OF ROOT SYSTEMS

6.1 Review of methods

One of the primary aims of this trial was an examination of the effects of tillage on crop development, both shoot and root. Interest was focussed on a quantitative assessment of root development and its vertical distribution. The initial problems were to decide not only how to collect samples, but also what to measure and how. A survey of available methods and their limitations was done prior to drilling 1968.

Schuurman and Goedewaagen (1965) have described excavation methods; the monolith, pinboard and profile mapping methods require extensive preliminary excavation; they are slow, disruptive to the growing crop and provide pictorial data of root distribution, not quantitative data.

Radioisotopes have been tried in an attempt to avoid the labour and disruption inherent in other methods. Burton, De Vane and Carter (1954), Fox and Lipps (1960) and Hall et al. (1953) have all injected $P_{32}$ into the soil and recorded specific activity in the shoots. $P_{32}$ was selected due to its mobility in the plant and its relative immobility in the soil; it is also readily detected. However, large doses are phytotoxic, its specific activity diminishes in time and it is inversely related to the soil phosphate level. This technique is thus limited because the specific activity in the plant is dependent on the
site, and the rate of uptake by the plant after the root system has come into contact with the radioisotope. Injected at specific vertical and lateral intervals, counts on the shoot matter establish the extent and rate of root penetration. Apart from the practical problems associated with large scale use of this technique it failed to provide adequate quantitative data of the type required on South Road.

Racz et al. (1964) and Halstead and Rennie (1965) injected P$_{32}$ into plants and measured the specific activity of soil cores. About 3% of the P$_{32}$ activity was translocated to the roots of a 40 day old plant, but only 1% was translocated in the case of a 60 day old plant. Subject to careful experimentation this provided an adequate measure of the P$_{32}$ activity for different soil horizons and hence a measure of the vertical distribution of roots in relation to the P$_{32}$ activity of the surface horizon. The total P$_{32}$ activity of the root system was determined by the dose rate and plant translocation and was not related to root size except that the bigger the plant the more dilute the P$_{32}$ activity. Quantitative measures have not been made with this method even in the improved form (Rb$_{86}$ instead of P$_{32}$) developed by Ellis and Barnes (1968), Russell and Ellis (1968) and Newbould et al. (1970). This technique did succeed in bypassing two of the major problems associated with other methods: the fracture and loss of fine rootlets and the requirement to distinguish between live and dead root.
Schuurman and Goedewaagen (1965) described augers and soil coring devices for taking small samples. Welbank (1968) has used a powered hollow auger but found it less satisfactory than the coring system. Coring devices vary from putting-hole corers, through hammer operated tubes to the highly sophisticated truck-mounted drilling rig described by Kelley et al. (1947). Boehle et al. (1963) used the hydraulics of a heavy tractor to sink and extract his tubes. Both Kelley and Boehle’s designs were too cumbersome for plot work, particularly in the presence of a growing crop. At the opposite extreme, the putting-hole corer was limited to 15 cm horizons and the horizons failed to fracture consistently in the required plane. Williams and Baker (1957) hammered in coring tubes with mallets; Stace and Palm (1963) used a sliding weight or an electric hammer. Welbank (1968) used a motor breaker to drive in his sampling tubes. Between these extremes there were compromises capable of adaptation to the particular requirements of the South Road trial. Coring tube design was basically similar for most operations; Stace and Palm recommended an external flair in addition to the internal relief and agreed with Welbank over the beneficial effects of lubrication on difficult soils. Williams and Baker (1957) found that extraction of the cores was difficult from their tube, hence they used a split tube held together by its removable cutting shoe – this design considerably weakened the corer. Welbank (1968) used a split brass liner within the sampling tube: this overcame the dual
problem of core extraction and disintegration. Welbank (1968) found that his device worked satisfactorily and compaction of the core within the tube was generally less than 2-3%.

After extraction of the soil core the roots must be separated from the soil. The first stage in this process often consists of soaking the core in water, sometimes with Calgon added (McKell et al., 1961; Fribourg, 1953; Barley, 1955; Troughton, 1951). Barley hastened the dispersion of soil aggregates by exposure to a high speed stirrer for thirty seconds. After adequate dispersion, the fine and coarse soil fractions have to be removed. The general principle involves washing the fine fraction through a sieve and decanting the roots off the coarse fraction. McKell et al. (1961), Barley (1955) and Cahoun and Morton (1961) decanted off both roots and fine fraction onto a sieve which retained the roots. McKell et al., Fehrenbacker et al. (1955), Fribourg, Cahoun and Morton and Williams and Baker have all described labour-saving gadgets for these jobs suited to their own particular soils and other requirements. Loss of roots under high water pressure and with large sieve meshes can happen with all these methods. Furthermore, long roots are not easily decanted off coarse materials as they tend to get trapped; removal of the fine fraction first, eases decantation of the roots. Mixed up with the roots are other organic particles; some of these may be skimmed off – the specific gravity of roots is about one so they tend to be suspended
in water, whereas dead organic matter tends to float. Generally the sample requires further laborious cleaning before it is ready for actual measurement.

Length, volume, and dry matter mass have all been used as measures of root systems. Dry matter has been measured by air drying the cleaned sample (Welbank, 1968; Welbank & Williams, 1968). Williams and Baker (1957) commented on the additional requirement for 'loss on ignition' as a means of determining the mineral tare content of the cleaned root sample. Volume measurement by displacement of water after spin-drying was used by Welbank (1968). Newman (1966) commented on the inaccuracies associated with the use of volume and diameter measurement to obtain length. Melhuish and Lang (1968) sectioned cores after impregnating them with resin and counted the number of roots visible on each surface; this provided data on root distribution, volume and surface area. Others have measured length direct, using graph paper and a small subsample which was then weighed. Newman (1966) described an indirect technique for use on root length. Of these three measures both dry mass and volume depend on clean samples obtained by hand removal of extraneous organic matter, seeds, mineral particles and other detritus. Unless dead root matter is identified as such and removed, it too will bias the results. Measurement of length, by Newman's method, avoids the need for cleaning.
Experimental Work

6.2a Measurement of root length

The technique was divided into three phases:
- Field sampling
- Root washing
- Root length measurement

Field equipment (Plate 1) was developed by the NIAE (Scottish Station) for this work. The coring tubes were thin, three inch O.D. mild steel water tubing; welded to the base was a cutting shoe, the weld being shaped to form an external flair. This cutting shoe (3" O.D.) was thicker metal than the tube, consequently it provided the internal relief recommended by Welbank and Williams (1968). The shoe was sharpened to a concave point and strengthened by infilling with tungsten carbide. The tube's driven end was drilled for extraction with a tommy bar and strengthened with a quarter inch welded collar. The manually operated Roadall M2A Miracle concrete breaker (Plate 1) provided the driving force: its pick point was pinned into a dolly which fitted the head of the sampling tube. The tube was driven into the ground by a downward thrust of the Roadall on its shaft.

Sampling was based on Welbank's recommendations (1968): four cores per plot, two between and two within the drills. Each core was divided into three equal horizons after removal from the sampling tube, then the samples were bulked by horizons. In 1969 and 1970 the total tray contents were weighed before being crumbled and mixed.
Shoot material was removed and roots broken into small sections prior to the removal of a weighed subsample.

The subsample, after soaking, was dispersed by a Citenco variable speed stirrer (Plate 2), before being washed onto an 8 inch 30 gauge sieve. The sieve was placed under a sprinkler system to remove the fine soil fraction (Plate 3). The sieve's contents were washed into a sedimentation tank and the roots decanted back onto the sieve (Plate 4). The sediment was washed and a further decantation carried out. The coarse sediment was thrown out and the root material in the sieve was washed into a beaker before being filtered through a buchner funnel (Plate 5). The sample was thus concentrated on a filter paper which was carefully folded and stored at -5 degrees C.

Newman's method (1966) was used for root length measurement. It is based on the arithmetical relationship between the length of an unknown quantity of root and the number of times the roots intersect lines of known fixed length within a specified area. The system of regular fields was chosen; the sample tray was black perspex, with 4.5 m of lines etched in white (Plate 6). The intersections were counted by passing the objective of a microscope, on a racked swinging arm, over the tray (Plate 7); the magnification was 5 x 1.25. An intersection was recorded if any part of a root touched an etched line; only those roots that appeared to have been physiologically active at the time of sampling were counted.
Various tests were carried out on the methods to test their accuracy. They were conducted after the initial year so that the results benefited from the first year’s experience and also the use of the equipment developed as a result of that experience.

**Methods checks**

**Tube compaction**

Throughout the work the depth of sampling was marked on the outside surface of the sampling tubes; this provided a means of judging the correct sampling depth. After plunging the cores from the tubes they were divided into the three horizons. These were measured with a ruler and were seldom more than one centimetre different from the theoretical length. The variations that did occur were random and depended on uneven ground level and imprecise fracture of the core at the internal relief.

**Loss of roots**

The Letcombe method with $\text{Rb}_{86}$ was developed partly because washing roots with water may destroy the smaller roots. The aim of this check was to examine the loss of root in the second phase of the sampling system.

Zephyr barley seed was planted in a coarse, abrasive soil in 350 ml polypots. After four weeks half of the samples were placed in a bowl of water and the mineral matter dispersed by gentle shaking. The roots together with attached particles of soil were then measured for length as described earlier. The roots were then mixed
with 300 g of soil before being exposed to the washing process used on the field samples. The roots extracted by this process were then measured for length once more. Two weeks later the same procedures were adopted with the remaining samples; in addition to total length of root, counts were taken before and after washing on the number of intersections recorded by lateral roots within the sample. This was designed to establish if root loss through washing was selective, and varied according to root size.

**Results**

92.2% ± 1.75 of the total length of root was extracted for measurement after washing. 92.3% ± 2.30 of the laterals survived the process. Consequently less than 8% of the root length was lost in washing and there was no difference due to root size.

**Newman's method**

A further check was carried out to test the reliability of this form of Newman's method. Known lengths of 5 amp fuse wire were cut into small pieces, spread out in the etched sampling tray and then the intersections were counted. Five lengths were counted 5 times; after each count the wires were redistributed. The mean of the five counts was compared with the known actual length.
Results

<table>
<thead>
<tr>
<th>Length of wire</th>
<th>Mean length by intersections</th>
<th>% error in method</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 cm</td>
<td>116 cm</td>
<td>+ 16%</td>
<td>4.7%</td>
</tr>
<tr>
<td>200 cm</td>
<td>203 cm</td>
<td>+ 1.5%</td>
<td>5.7%</td>
</tr>
<tr>
<td>300 cm</td>
<td>299 cm</td>
<td>- 0.3%</td>
<td>3.0%</td>
</tr>
<tr>
<td>400 cm</td>
<td>420 cm</td>
<td>+ 5.0%</td>
<td>2.4%</td>
</tr>
<tr>
<td>500 cm</td>
<td>517 cm</td>
<td>+ 3.4%</td>
<td>0.9%</td>
</tr>
</tbody>
</table>

The high overestimate associated with the 100 cm sample resulted from uneven distribution of wire between the margins of the tray and the area occupied by the etched lines. The small mean overestimate was approximately equal to the percentage of the etched area occupied by the width and length of these etched lines. This explanation was further tested; in 1968 a transparent perspex tray was used. The lines were drawn onto it with a waxed pencil, consequently they were much thicker and occupied a larger proportion of the area. This same test was carried out and the overestimate was much higher. All results have been corrected according to the type of tray used.

Sampling details for main experiment

<table>
<thead>
<tr>
<th>Dates</th>
<th>Depth sampled</th>
<th>Replicates</th>
<th>Subsample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/11 June 1968</td>
<td>30 cm</td>
<td>5-8</td>
<td>200 g</td>
</tr>
<tr>
<td>24 July/1 Aug 1968</td>
<td>30 cm</td>
<td>2-8</td>
<td>200 g</td>
</tr>
<tr>
<td>9/17 June 1969</td>
<td>36 cm</td>
<td>1-8</td>
<td>300 g</td>
</tr>
<tr>
<td>14/22 July 1969</td>
<td>36 cm</td>
<td>1-8</td>
<td>300 g</td>
</tr>
<tr>
<td>11/15 Aug 1969</td>
<td>36 cm</td>
<td>1-8</td>
<td>300 g</td>
</tr>
<tr>
<td>18/22 May 1970</td>
<td>36 cm</td>
<td>1-8</td>
<td>300 g</td>
</tr>
<tr>
<td>27 July/1 Aug 1970</td>
<td>36 cm</td>
<td>1-8</td>
<td>300 g</td>
</tr>
</tbody>
</table>
Results (Tables 39-48)

The results have been converted from length of root (cm/g of soil) to length of root (cm/cc of soil) using the soil mass data collected in 1969 and 1970 and the bulk densities measured in 1968.

The June 1968 data (Tables 39 & 40) was limited to four blocks; there were no tillage differences associated with the mean length of root in the top 30 cm of soil, though there was an indication that in the 20-30 cm horizon root growth was more prolific on the deep ploughed treatment. In June 1969 (Tables 42 & 43) all blocks were sampled; not only was a larger (300 g) subsample processed but the efficiency of the technique had been improved too. There was a 25% reduction in the mean length of root on the direct drilled treatment in the top 36 cm. Horizon differences were more pronounced than in the previous year: in the top 12 cm, root length on the direct drilled treatment was reduced by nearly 30% compared with the other treatments. In the middle 12 cm, growth on the deep and chisel ploughed plots was similar and better than the growth on the other two treatments. The middle horizon contained the level at which a plough pan was expected to develop on the shallow ploughed treatment. The NIAE bulk density data (Table B) provided evidence of this. The data for the 24-36 cm horizon confirmed the trend in 1968 and further demonstrated that root growth within a horizon might be improved by prior soil disturbance in the form of tillage. In 1970 (Tables 46 & 47) there was a 40%
reduction in the mean length of roots on the direct drilled treatment. The sampling period was in the middle of May, shortly after full emergence, consequently this data was taken at an earlier growth stage than in the previous two years (tillering stage). Compared with deep and shallow ploughing, the direct drilled treatment had 44% less root length in the top horizon; chisel ploughing was intermediate in growth. In the middle horizon the direct drilled treatment produced a smaller length of root than the other treatments and in the bottom horizon there were no major differences; however it appeared that deep ploughing had slightly more root than direct drilling.

The vertical distribution of root length for the top, middle and bottom horizons in June 1968 and 1969 was 56, 32 and 12% respectively, whereas in May 1970 the corresponding figures were 75, 19 and 6%. The actual lengths of root were similar for mean growth in 1968 and 1969, just over 2 cm/cc of soil, whereas in 1970 the value was only 0.72 cm/cc. This demonstrated that soon after emergence was a period of rapid root growth; it was also a period in which direct drilling appeared to depress root growth.

In 1969 data was collected in July (Tables 42 & 44) after ear emergence. Direct drilling continued to depress root growth in comparison with deep and chisel ploughing. The difference in length between the means was still the same as in June. There were no significant tillage differences in the middle horizon ($P \neq 0.05$) but the June
trends were still evident. There were no differences in the results for the bottom horizon. The vertical distribution had changed: by mid-July it was 47, 36 and 17%, indicating a shift towards deeper roots as the growing season progressed.

In late July/August (Tables 39, 41, 42, 45, 46, 48) a further root length measure was taken each year. There were no appreciable differences in the mean root growth of the cultivated treatments, but direct drilling reduced length by 16%. This reduction was concentrated in the top horizon. There were no large differences in the middle horizon in 1968 and 1970; however length appeared reduced on the direct drilled treatment. In 1969 the differences were significant ($P = 0.001$), deep and chisel ploughing producing more root than the other treatments. The deep ploughed treatment produced the most root in the bottom horizon though this result was only significant ($P = 0.05$) in 1968. The vertical distribution for the three horizons was 56, 27 and 17% in 1968, 44, 36 and 20% in 1969 and 58, 27 and 15% in 1970. The mean lengths were 2.64, 1.48 and 1.45 cm/cc for the three years respectively. The pattern of rooting was similar in 1968 and 1970, whereas the amount of roots were similar in 1969 and 1970.

Nitrogen had no effect on mean root length for the first sampling period in either 1968 or 1970, but in the latter year sampling took place only three weeks after nitrogen was applied, and the intervening weather was dry.
In 1969 added nitrogen increased mean root growth: in this year there were nitrogen/horizon interactions, as in the top horizon nitrogen increased root length, but in the bottom horizon it reduced root length. In 1970 there was no effect in the top and bottom horizons, but in the middle one, applied nitrogen reduced root length from 0.57 to 0.30 cm/\(\text{cm}^3\). In July 1969 the root results demonstrated that nitrogen increased root length all through the top 36 cm, the response being strongly quadratic. The final sampling in each year demonstrated large increases in root length resulting from application of nitrogen. The mean responses to 150 kg N/ha were rises of 80% in 1968, 54% in 1969 and 51% in 1970. By August the root length response to applied nitrogen was positive in all three horizons, even between the N3 and N4 rates.

There was some evidence that in the absence of applied nitrogen, shallow ploughing produced the greatest root length, but its response to nitrogen was generally the smallest. The response to applied nitrogen with direct drilling was similar to that with deep and chisel ploughing.

6.2b Root length below depth of cultivation (36-54 cm)

The previous work determined the production and vertical distribution of roots in the top 36 cm; Welbank (1968) and others have shown that cereal roots penetrate to much greater depths, and it was apparent from the previous sampling that this was true on the South Road
trial too. This work was designed to examine the production of roots beneath the zone of the deepest cultivation. For practical reasons the zone examined was limited to the 36-54 cm horizon.

The top 36 cm of soil was removed in the normal sampling tubes, then longer ones were driven in a further 18 cm. Because of the low content of roots in the 24-36 cm horizon it was assumed that the root content would be even smaller, and thus more difficult to measure, in the 36-54 cm horizon. As sampling at this depth was limited, the whole 18 cm core was used in the separation process.

**Sampling details**

<table>
<thead>
<tr>
<th>Date</th>
<th>Replicates</th>
<th>Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 Aug 1969</td>
<td>2, 3 &amp; 4</td>
<td>All tillage at N1 &amp; N4</td>
</tr>
<tr>
<td>7 Aug 1970</td>
<td>1, 2, 5 &amp; 6</td>
<td>All tillage at N1 &amp; N3</td>
</tr>
</tbody>
</table>

**Results**

Tillage had no effect on the length of root in the 36-54 cm horizon; nitrogen increased root length. About 12% of the total root length in the top 54 cm was in this horizon. These results suggest that the influence of tillage on roots was particular to the zones within which tillage was physically operating and that there was no reason to suspect that tillage had any effect in this trial on the actual depth of rooting.

6.3 **Measurement of root diameter**

During 1969 and 1970 root diameter measurements
were made on some of the material used for root length measurement. After completing the latter, the sample was spread out in a red perspex tray (Plate 8). This contained a number of arcs etched in black; these followed the paths described by the microscope objective if it were swung on a number of different radii. The eyepieces were changed to (x 14), one being fitted with a linear graticule. The objective was swung over one arc; the number of roots crossing the etched arc were recorded on one tally counter and the sum of the diameters of the roots recorded on another after measurement with the linear graticule. Where sufficient root material was available, 100 intersections were measured. The results were changed to metric standards after calibrating the graticule against a metric rule.

**Sampling details**

<table>
<thead>
<tr>
<th>Date</th>
<th>Replicates</th>
<th>Horizons</th>
<th>Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td>14/22 July 1969</td>
<td>1-8</td>
<td>Top &amp; bottom</td>
<td>All tillage at N3</td>
</tr>
<tr>
<td>18/22 May 1970</td>
<td>1-8</td>
<td>Top only</td>
<td>All tillage at N2 &amp; N4</td>
</tr>
<tr>
<td>27 July/1 Aug 1970</td>
<td>1-8</td>
<td>All three</td>
<td>All tillage at N1 &amp; N3</td>
</tr>
</tbody>
</table>

At the July 1969 sampling, data was collected for all subplots in block 3; this provided a measure of the nitrogen effect.

**Results (Tables 50-53)**

Root diameter in July 1969 was largest on the direct drilled treatment. Root diameter on the shallow ploughed treatment was 6% larger than the mean of the chisel and deep ploughed treatments. There were no differences in the
bottom horizon. In 1970 the top horizon results for the early sampling period produced similar but more pronounced effects. By the end of July, following a wet period, there were no differences in root diameter attributable to tillage. Nitrogen effects were measured on all three occasions; there were no consistent differences or trends. **Derived data** *(Table 54)*

The root length data and the diameter data were combined to provide information on the root surface area and root volume.

### 6.4 Discussion

The anchorage and absorptive efficiency of the root system may limit the economic potential of the crop. Anchorage and absorptive efficiency were not measured in the South Road experiment, instead work was limited to the root system's physical characteristics. Muzurak and Pohlman (1968) measured root length, weight and number and found that length was the most sensitive to soil physical conditions. Aubertin and Kardos (1965) found that root volume, length and weight were significant indices of root response to oxygen levels and pore rigidity, and that these parameters were closely correlated among themselves. Goss and Walter (1969) demonstrated that two different ballotini systems produced similar dry weights of shoot and root, similar root volumes but different root numbers and root axes' length. Measurement of root length on South Road demonstrated a root length response to tillage.
Both length and surface area are terms used by plant soil physicists and physiologists in quantifying root function (Nye, 1966). Limited diameter data was used to derive surface area and volumes for the South Road trial. Both Lemon and Weigard (1962) and Gardner (1960) have demonstrated that soil conditions which depress crop growth may increase root diameter and consequently variates dependent on it. Furthermore, as increased root diameter lengthens the oxygen diffusion barrier within the plant, so the critical concentration of oxygen at the root surface is higher with thick roots. As Russell and Sandison (1966) found that the coefficient of variation for the uptake of nutrients was less per unit volume, or area, of root than per unit length, inclusion of diameter measures was an important part of this work. Of the parameters mentioned in Table 54 root length and surface area appeared to be physiologically useful indices of root growth.

Root length and surface area have several properties which may affect the efficiency of the root system: apart from size or extent, there is vertical distribution, depth of exploitation and growth rate. As maximum depth of rooting was not measured on South Road, the size and vertical distribution exclude a small fraction of the root system. Sampling to a depth of 54 cm provided no evidence of tillage differences below the depth of the deepest tillage treatment, consequently exclusion of this small fraction appeared unlikely to seriously affect the results.
Welbank and Williams (1968) have sampled deeper but the roots below this depth were only a minute proportion of the total and the sampling errors were very high.

Due to the limited number of sampling periods it was impracticable to draw growth curves of the changes in root length. It was apparent that the highest percentage differences occurred at the earliest time of sampling. In 1969 the late summer decline in root length was marginally higher on the tilled treatments. Welbank and Williams (1968) have established that maximum root production precedes maximum shoot production, consequently early differences in root production, as occurred on South Road, may be particularly important. Prebble (1970) found that, in the absence of an 'overburden', root penetration of the sides of the drill slit was reduced, particularly if the sides were smeared. An 'overburden' was created on South Road by rolling the direct drilled plots after drilling.

The importance of differences in vertical distribution is difficult to assess; the topsoil is generally more fertile than the subsoil, but it is more susceptible to drying-out, whereas the latter is more prone to waterlogging. Although differences in vertical distribution were recorded in South Road, these differences were of direct relevance only if they resulted in overall differences in root length. The main result of this root work was a reduction in length on the direct drilled treatment.
In the following investigation into possible and probable causes of root length differences induced by tillage, climatic and genetic effects have been disregarded. Little work was done on biotic effects other than measurement of take-all (Section 7). The major differences in root length appeared before plant infection was serious, hence it has been assumed that take-all was not primarily responsible.

Roots react to chemical stimuli according to the type of stimulus, its concentration and its distribution. Throughout the experiment tillage treatments received similar application of nutrients and the 1967 soil analysis confirmed that the initial supply was similar for all treatments. In autumn 1969 the vertical distribution of pH, P and K was examined (Appendix 4b) on the direct drilled and shallow ploughed treatments. The results indicated that, although there were interactions between nutrient levels and vertical distribution, the mean nutrient level of the top 20 cm was the same for both treatments. The importance of minor differences in vertical distribution of nutrients is as difficult to assess as the importance of differences in root distribution. Since mean nutrient levels were similar and there was an overall annual application of both P and K before drilling, these differences were considered to be relatively unimportant.

In waterlogged soil the production of gases such as ethylene in concentrations detrimental to root growth has
been demonstrated by Smith (1969) and Smith, Restall and Robertson (1970). Smith also found that the addition of nitrogen reduced the evolution of ethylene on a sandy loam soil. If ethylene toxicity was the cause of the tillage root length differences then an interaction between tillage and applied nitrogen would be expected, since nitrogen would partly overcome the depressant effect of the ethylene inducing treatment. There was no evidence of such an interaction so it is concluded that ethylene toxicity is not the major cause of root length differences. Smith found that, although ethylene production depended on microbes functioning in anaerobic conditions, production was negligible at low soil organic matter contents; as continuous cereal growing tends to reduce soil organic matter, the likelihood of ethylene toxicity occurring is reduced.

Eavis (1965) has shown that carbon dioxide is also detrimental to root growth - it tends to accumulate if air-filled porosity is small. Low air-filled porosity, limiting oxygen and aeration stress are products of the same physical conditions. The simultaneous accumulation of carbon dioxide is one other side-effect of a soil's physical state that retards root growth. As toxic or narcotic chemical stimuli tend to result from a particular soil state, it was the effect of tillage on the soil's physical state that was primarily responsible for root length differences on the South Road experiment.

Four major soil physical properties affect root
growth; these are soil temperature, strength, moisture content and aeration. No measures of soil temperature were taken on the South Road experiment; temperature is a highly variable property exhibiting marked diurnal fluctuation in summer. Richards et al. (1952) quote a Q10 of 2 for growth between 10 and 20 degrees C, hence even small temperature differences may have a considerable influence on growth rate. If other factors are similar, a wet soil is generally accepted to be colder in spring than a dry one and there was evidence of small soil moisture differences on South Road due to tillage. In 1968 and 1969 there was no evidence that germination or emergence were affected by tillage but soil temperature may have determined the subsequent growth rates.

An increase in soil water raises the specific heat and conductivity but reduces the diffusivity of a soil, consequently wetter soils react slower but more uniformly to changes in temperature (Baver, 1966). In spring the wetter soil heats up less during the day but because of its lower diffusivity it cools down less at night. On the South Road experiment the moisture content differential was greatest in 1970: the direct drilled treatment contained 5% more water than the mean of the other treatments. Assuming a dry specific heat for soil of 0.20, then 45 calories are required to raise 100 g of soil solids and 25 g of water through one degree Celsius. For a moisture content 5% higher the same amount of heat would raise both the solids and the increased water content
through 0.85 degrees Celsius. The mean soil temperature at Bush (1 mile away) rose 3.5 degrees Celsius during the month prior to early root sampling in 1970. The calculated differential for this rise is $0.15 \times 3.5 = 0.5$ degrees Celsius. As the temperature range was within the 10-20 degree range mentioned by Richards et al. (1952), the estimated increase in growth, based on a Q10 of 2, for this temperature differential is 5%, but the actual difference was 75%. This argument disregards complications due to latent heat, conductivity and diffusivity, but changes in conductivity do not alter the mean temperature and diffusivity changes are small at small moisture differentials. Since soil temperature is affected by soil moisture, the other physical properties of the soil appear to be more directly involved in limiting root growth on South Road.

Soil strength, water and air are interrelated. A soil consists of spaces and solids; the spaces are the gaps between soil particles, aggregates and clods. Part of the space is occupied by water, the remainder by air. The volume ratio of liquid to gas is a transient feature subject to drainage, rainfall and other factors. Both phases have three characteristics affecting plant growth, namely the volume they occupy, their conductivity and intensity. Soil strength is related to the movement of soil particles when a soil is loaded. This movement may result from solids being compressed, thereby eliminating spaces, or from plastic flow or particle rearrangement.
Wiersum (1957) pushed a steel wire into 20 mm diameter test tubes filled with sand; he was unable to do this with 5 mm diameter test tubes as these presented a more rigid system, particle rearrangement was opposed by strong frictional forces.

Changes in bulk density or moisture content affect the three main soil physical conditions simultaneously. As surface tension forces are higher in smaller pores, so water drains more readily from the larger soil pores. As water is removed, soil moisture content falls and air replaces the water. Since water is held more strongly in the smaller pores, the mean soil moisture tension rises and correspondingly the availability of the residual water falls (Gingrich and Russell, 1957). Conversely, when a soil is irrigated water tends to trap air in pockets, consequently the conductivity of the remaining air is reduced due to its poor diffusion in water. Eavis (1965) has demonstrated the effect of aeration stress on root growth. Aeration stress results from the reduced volume of air containing a reduced partial pressure of oxygen. As soils tend towards anaerobic conditions so carbon dioxide and other toxic compounds accumulate and generally augment the depressant effect of aeration stress on root growth. Thus changes in moisture content affect the content, conductivity and intensity of both water and oxygen. Both moisture content and air-filled porosity are transient characteristics because heavy rain can quickly change the plant environment from water stress to
aeration stress. Erickson and van Doren (1960) and Letey et al. (1962) have demonstrated that even short periods of aeration stress may severely inhibit plant growth. The former, in a glasshouse experiment on peas and tomatoes, demonstrated that a 24 hour oxygen deficient period reduced yield of tomatoes by up to 50%.

The NIAE soil data (Tables A & C) on moisture content and air-filled porosity is only valid for the actual time of sampling whereas the root data are measures of performance up to the time of sampling. The relationship between these two sources of data is indirect but if soil data indicates that tillage produces soils with different stress susceptibilities then deductions can be made of the probability of stresses actually occurring. Consequently roots on a tillage system with a low air-filled porosity are more susceptible to aeration stress in wet periods than roots on treatments with a higher air-filled porosity. For this argument to be valid it follows that periods of aeration stress or moisture stress must be identified within the growing season. Vomacil and Flocker (1961) and Baver and Farnsworth (1940) have quoted limiting air-filled spaces of ten percent volume per volume. This is no absolute figure as it varies with crops: rice and others translocate oxygen (Greenwood, 1968), consequently their requirement from the soil is reduced. Growth is not only determined by air-filled porosity, it also depends on the partial pressure of the air in the space and the conductivity. But a reduction in air-filled porosity
reduces the partial pressure of oxygen and the conductivity of air in the soil so the adverse relationship between aeration stress and root growth tends to be aggravated. If air-filled porosities below 10% have been recorded, this is evidence that aeration stress may have occurred.

Sandy soils have large pores with only a few weak water bonds; as water is easily removed sands tend to become weaker as they dry out. Soils with a mixture of particle sizes tend to become stronger as they dry because their numerous water bonds develop high surface tension forces. An increase in soil moisture tension can also be achieved by reducing the number of weak bonds in a soil through compaction. If the mean pore size is reduced, this lowers the proportion of pores drained at a given soil moisture tension. Another effect of compaction is the gradual elimination of air spaces into which soil particles can move when loaded (Youard, 1957), so compaction alters the strength of a soil, its air content and its water holding characteristics. Compactive effects were expected in the South Road trial due to lack of tillage on one of the treatments. Compaction was measured by Soane together with the proportion of the ground surface affected by passage of machines and implements.

Both Eavis (1965) and Soane (1969) have reviewed work on the effect of soil physical conditions on the growth of plants and crops. It is established that plants fail to grow satisfactorily if their growth medium is impenetrable or either oxygen or water stress persist. In a rigid
ballotini experiment, with two pore sizes, Goss and Walter (1969) found that plants grown in the smaller pores had shorter roots but more laterals. Aubertin and Kardos (1965) compared the growth of roots in rigid and non-rigid pore systems with two sizes of pore. On both systems the large pores had similar root lengths, numbers and weights, but in the smaller pores on the rigid system these three parameters were drastically reduced. Wiersum (1957) found that penetration in a rigid system is limited to pores wider than the roots but in non-rigid systems root penetration was dependent on the ability of roots to exert axial and abaxial forces greater than the frictional and other cohesive forces of the surrounding medium. Compaction has two components, it reduces the pore size but it also may increase the mechanical strength of the medium. Gill and Bolt (1955) and Eavis (1965) have demonstrated that wrinkling and folding of root cell walls is a response to mechanical impedance. Taylor and Gardner (1963) and Taylor and Ratcliffe (1969) have demonstrated inhibition of root growth and penetration as soil strength was increased. Eavis (1965) measured mechanical strength in soil with a penetrometer for three bulk densities at different soil moisture tensions. The mechanical strength was increased both by high soil moisture tension and high bulk density; in addition there was a positive interaction between these factors. For 'optimal' aeration and moisture contents root length was inversely related to soil strength. Eavis deduced that
values below the regression line of root length on soil strength resulted from water or aeration stress. As compaction is used to increase soil strength (Youard, 1957), compacted soils suppress root growth by forming a physical barrier, also they are particularly susceptible to aeration stress resulting from their low pore volume and high proportion of water-filled pores.

Soane's data on soil mechanical strength (Table D) refers to autumn 1970 only. His data demonstrate that direct drilling, compared with tillage, increased cone resistance in the top horizon by 131% preharvest, but only 66% post-harvest; the effect of harvest tracking was greater on the less compacted treatments. Bulk density data for the earlier occasions indicated that direct drilling produced the most compact top horizon, so it is deduced that mechanical strength was generally high on this treatment. This deduction is substantiated by the consistency with which operators, unfamiliar with the experiment's design and treatments, soon discovered that taking root samples was harder work on certain plots: these invariably had been direct drilled. These data demonstrate that tillage treatments produced soils of different strengths and previous work has shown that root growth is impeded on soils of high mechanical strength (Eavis, 1965; Bertrand & Kohnke, 1957).

Soane's data on air-filled porosity demonstrates the susceptibility of treatments to aeration stress. Below is a summary of the air-filled porosity in the top 12 cm of soil.
<table>
<thead>
<tr>
<th>Date</th>
<th>Tilled</th>
<th>Direct drilled</th>
</tr>
</thead>
<tbody>
<tr>
<td>25/30 April 1968</td>
<td>20.3%</td>
<td>9.9%</td>
</tr>
<tr>
<td>21/28 May 1969</td>
<td>17.1%</td>
<td>4.0%</td>
</tr>
<tr>
<td>20/27 May 1970</td>
<td>23.0%</td>
<td>9.1%</td>
</tr>
<tr>
<td>23/26 July 1968</td>
<td>13.6%</td>
<td>7.4%</td>
</tr>
<tr>
<td>16/21 July 1969</td>
<td>38.2%</td>
<td>26.2%</td>
</tr>
<tr>
<td>20/29 July 1970</td>
<td>18.5%</td>
<td>9.5%</td>
</tr>
</tbody>
</table>

These data demonstrate large differences in air-filled porosity resulting from tillage. They also indicate that after direct drilling, air-filled porosity was not only low but it was often in the limiting region of 10% reported by Vomacil and Flocker (1961) in their review of previous work. As data was collected in dry weather for technical reasons, these figures may not include the minimum figures reached temporarily after rain. The low volume for direct drilling did indicate that it was more susceptible to aeration stress both in intensity and duration; however, the limiting value is lower on this treatment than on the others. Greenwood (1968) has pointed out that for a given diffusion rate the air-filled porosity of a soil with large pores is greater than one with the same volume of gas distributed in smaller pores, since gas-filled pore space is more effective in aerating the soil if pore size is small. As replenishment of air is limited by rate of diffusion a smaller gas-filled volume can satisfy the aeration requirements of plants on compacted soils.
Compaction reduces diffusion of oxygen from the atmosphere into the soil spaces because it disrupts the continuous channels and increases the proportion of pore space occupied by water. Diffusion of air in water is ten thousand times slower than in air, so in wet conditions replenishment of air is slower in compacted soil with the result that partial pressure of oxygen in the gas-filled pore space falls and carbon dioxide accumulates. Eavis (1965) demonstrated that a reduction in partial pressure of oxygen from 21% to 3.5% decreased root length by 63%. If 15% carbon dioxide was introduced it had little effect on root length at the low oxygen concentration but it reduced root length by 42% for the high oxygen concentration. On treatments with low air-filled porosities there were periods when air pore space was small, and consequently both the partial pressure and diffusion rate of oxygen were small too. To aggravate the situation further a small air-filled porosity results from a more compact and probably rigid soil system, so plants may also be impeded mechanically. In compacted soils aeration stress operates in wet periods and mechanical impedance is particularly serious in dry periods. Either can be lethal to the crop, but in many agricultural situations neither is lethal but both operate together in varying proportions and intensities through the growing season to the detriment of the crop.

The following examination of South Road data for root length and soil physical differences excludes soil
moisture content. There was a tendency for mean soil moisture content to be similar on the tilled and untilled treatments.

Tillage treatments had several major effects on roots:
1) Direct drilling produced less root length than the other treatments, the reduction being principally in the top 12 cm.
2) Deep ploughing generally produced more root length than the others in the 24-36 cm horizon.
3) Shallow ploughing tended to have the same root length in the top 12 cm as the other tilled treatments but less root in the next 12 cm horizon in 1969.
4) Root diameter (top 12 cm horizon) was largest with direct drilling.

In comparison with other tillage treatments, direct drilling increased cone resistance in autumn 1970, and produced the highest soil dry bulk density. An increased bulk density of only 12% at emergence may result in massive changes in soil strength and air-filled porosity. The reduction in the latter was 62%. In autumn 1970 direct drilling increased bulk density by only 5% but soil strength went up by 131%. Hence, a small bulk density increase on the direct drilled treatment had a large effect on two soil physical conditions known to affect plant growth. The effect of direct drilling on the soil was greatest in the top horizon but was sometimes present in the middle horizon too; this was to be expected as the effect of compaction is greatest near the point of
compaction. The increase in diameter of plant roots indicated that mechanical stress was operating too.

During the early part of the growing season the soil is still moist and relatively weak. Root growth was most affected in this period so it would appear that the soil strength differences were supplemented by aeration stress. The spatial occurrence of low air-filled porosity, high mechanical strength and high bulk density closely tallied with the reduction in root length on the direct drilled treatment, its increase in diameter in the top horizon and lack of difference in the bottom horizon.

The production of extra root length in the bottom horizon, resulting from deep ploughing, corresponded to a reduced bulk density and cone resistance in that horizon together with an improved air-filled porosity. In 1969 the roots on this treatment were possibly thinner than those on the direct drilled and shallow ploughed treatments. Reduced mechanical impedance and more aeration were probably responsible for root differences at this depth.

In 1969 shallow ploughing produced less root in the middle horizon than the other tilled treatments. Although soil parameter means for this horizon show no major differences, Soane's detailed data (1970) reveals massive changes in both bulk density and air-filled porosity within this horizon. A similar trend was detected in 1970. In 1970 shallow ploughing appeared to have the
largest root diameter in the middle horizon. Such variation within this horizon resulted from the ploughing depth for this treatment being at 20 cm, halfway down the horizon. Above the plough sole was a shallow layer of very low bulk density, and below it a relatively hard layer. The large variation in soil physical conditions within the 12-24 cm horizon with shallow ploughing resulted in variable root responses.

The mean root response to direct drilling on South Road was a reduction in length. Finney and McIlvenny (1970) and Newbould et al. (1970b) measured the length of seminal roots soon after emergence and found that length was reduced by direct drilling. Knight and Holmes (1970) measured soil parameters for Finney and McIlvenny; direct drilling increased soil bulk density in the 0-2", 2-4" horizons by 11 and 6% respectively. The corresponding reductions in air percentage were 32% and 19%. Direct drilling reduced the proportion of large pores. Penetrometer results on Newbould's trial indicated that direct drilling increased resistance at depths of 4 and 8 cm by about 400 and 350% respectively; deeper readings for the direct drilled treatment were off the quoted scale.

Results from Czechoslovakia (Stranak, 1968) and other European countries (Scharbau, 1968) indicated that direct drilling resulted in a more thorough exploration of the soil by roots both horizontally and vertically. Stranak (1968) found that compacted soils produced a larger root surface, more tillers and heavier grain yields. These
results tend to be associated with summers that are both hotter and drier than those generally experienced in Britain. Stranak (1968) explained that the close seed/soil and root/soil contact achieved in compacted soils increased uptake of nutrients and water. Some of the bulk densities quoted in Stranak's work were less than 1.00 g/cc, consequently it would appear that he was working on soils inherently lighter than those found on the South Road trial. Such soils would tolerate more compaction than the heavier, wetter soils characteristic of the South Road trial.

Although the overall root response to direct drilling on the South Road trial agreed with Finney and McIlvenny's results at Jealott's Hill (1970), and those of Newbould et al. (1970b) on the Weed Research Organisation Farm at Begbroke, there were marked differences in the vertical distribution of the root system. Finney and McIlvenny (1970) provided photographic evidence that lateral roots developed along the whole length of seminal axes in ploughed soil, but with direct drilling lateral development, although profuse, was limited to a shallow zone immediately below the seed. There were no differences in the adventitious root system due to tillage. Both Jealott's Hill and Begbroke experiments were harvested in 1969; they were sited on well-drained sandy loams in areas of similar rainfall and potential transpiration (MAFF, 1962). There was no ploughing data for 1968 at Begbroke (Newbould et al., 1970); a comparison between
untilled and cultivated with a tined implement to a depth of 15 cm indicated that the proportion of root system above 12.5 cm was 75.8 and 82.0% for the two treatments respectively. Ellis and Barnes (1969) concluded that there were no significant differences between treatments. In June 1969, although the top 12.5 cm contained 65 and 52% of the root system for the untilled and ploughed treatments respectively, within the top 23 cm the figures were 83 and 82%. Differences in the distribution of roots at Begbroke appeared to be small and rather variable.

Three forms of root response to direct drilling emerge from the literature and the South Road trial. For conditions in which cereal yields are increased by compaction (Stranak, 1968) root growth is increased by direct drilling. Compared with the Edinburgh trial, the Jealott's Hill and Begbroke results were obtained on lighter soils in drier areas. The results of the latter experiments resemble those induced by Goss and Walter (1969) in their investigation on the "effect of mechanical resistance on the growth of plant roots". Length of seminal roots (barley) in a rigid ballotini system was restricted by the size of pore but there was a corresponding increase in the number of seminals. The Jealott's Hill direct drilled roots presented a similar appearance. Knight and Holmes (1970) found that ploughing produced 60% more voids of suitable radius for unimpeded root growth. Although there is a close agreement between Goss and Walter (1969) and Pinney and
McIlvenny (1970), Stranak (1968) and Newbould et al. (1970b), on the South Road trial there was evidence of an actual restriction to root growth in the top 12 cm of soil with direct drilling. Aubertin and Kardos (1965) have shown that reduced pore size will limit both individual root length and also the number of roots. The mean air-filled porosity on the tilled treatments was 22% in the top 12 cm of South Road, compared with 28% for the top 4 inches at Jealott's Hill. The corresponding data for the direct drilled treatment was 11% on South Road and 21% at Jealott's Hill. But air-filled pores tend to be the larger ones, so a reduction in air-filled porosity is equivalent to reducing the ballotini size in Goss and Walter's experiment (1969), possibly to sizes found by Aubertin and Kardos (1965) to limit total root length. The probability of pore size being reduced to a size that would limit root growth was greater on South Road than at Jealott's Hill.

The reduction in root length with direct drilling on South Road was limited to the upper regions of the soil profile. There is evidence (Newbould, 1970a; Kuipers, 1970) that roots can traverse regions of dense soil and then proliferate in lower horizons. Holmes and Knight (1970) found that pores, although smaller with direct drilling, tended to form continuous channels. There was visual evidence on South Road of roots growing in worm channels. There is some evidence that the direct drilling treatment had the highest worm count (Appendix 5).
Because bulk density is a mean value, a soil generally contains weak regions in its profile, these regions being subject to root penetration. On South Road direct drilling produced a mechanical barrier that limited root growth in the top 12 cm but those roots that penetrated the barrier produced growth in the lower horizons that tended to be similar to that of the tilled treatments.

Welbank and Williams (1968) found that application of nitrogen in excess of 100 kg N./ha did not increase weight of root. On South Road root length was increased by applications in excess of 100 kg N./ha, possibly because this site was inherently less fertile than that used by Welbank and Williams. Although Welbank and Williams found that root weight reached a maximum before maximum shoot growth, there was no evidence on South Road that applied nitrogen affected root length earlier than shoot yield.

The nitrogen results produced four effects:
1) Root length was generally increased by application of nitrogen up to 150 kg N./ha.
2) Shallow ploughing resulted in the longest length of root in the top horizon at N1.
3) The increase in actual root length due to applied nitrogen was smallest with shallow ploughing.
4) The increase in actual root length due to applied nitrogen was similar for direct drilled, deep and chisel ploughed treatments.

Root responses are complicated in that positive
responses may result from the addition of a growth promoting agent, such as nitrogen (Welbank & Williams, 1968), but sometimes such agents result in negative responses (May, Chapman & Aspinall, 1965). Generally nitrogen increased root length, but early in the growing season, particularly in the lower horizons, root length was reduced by applied nitrogen; subsequently nitrogen increased length. Optimum root length is achieved if the increase in economic yield resulting from extra nutrient and water uptake is as large as the diversion of photosynthate to the roots. For conditions of plentiful nutrients and water a reduction in root length may increase the economic yield of the crop. On South Road in the absence of applied nitrogen shallow ploughing produced a large root system in the top 12 cm relative to the other treatments. The small root length response with shallow ploughing may have resulted from the diversion of nutrients and photosynthate to shoot and ear growth rather than to possibly superfluous root growth. Heavy grain yields are associated with reduced root:shoot ratios (Welbank & Williams, 1968). In 1968, compared with N3, N4 increased mean root length by 17% but grain yield by only 3%. Therefore an increase in root length, especially where the root system is well developed, does not necessarily result in larger yields.

Although the actual increase in root length due to applying nitrogen to the direct drilled treatment was similar to the increase with deep and chisel ploughing,
it occurred on a much smaller root system. If the size of a root system is limiting shoot growth, a given increase in actual root length increases the system to an extent inversely related to the original size of the system. Consequently for equal increases in root length the yield increase will be greater the smaller the system. But direct drilling produced thicker roots than the other tillage treatments, so the increase in surface area for a given increase in root length will be greater on the direct drilled treatment. Although nitrogen does not affect differences in root length between tillage treatments, at high nitrogen rates the small surface area differences between direct drilled root systems and the others tended to disappear.
TAKE-ALL INCIDENCE

7.1 Review

Take-all was assessed each year in relation to the various treatments. This disease is affected by tillage (Brooks & Dawson, 1966), fertilisers (Slope & Etheridge, 1967) and rotational practice (Slope, 1967; Shipton, 1967), and is known to reduce cereal yields (Slope, 1967). Both eyespot and sharp eyespot were assessed in 1968, but not in subsequent years; incidence of these diseases was sporadic and not related to treatments; this finding agreed with other local results (Gill, 1970).

Take-all is caused by the soil-borne pathogen *Ophiobolus graminis* which spreads by mycelial growth along living roots. Cereal roots may become infected if they come into contact with this fungus. The mycelium is composed of broad black 'runner' hyphae; these feed by means of thin colourless 'infection' hyphae which penetrate the roots (Garrett, 1956). In the absence of living root, the take-all fungus enters a saprophytic stage in which mycelium survives on the root and stubble debris of previously infected plants.

Apart from saprophytic survival *O. graminis* has other subsidiary survival mechanisms. Although it is primarily parasitic on cereals, Padwick and Henry (1933) and Padwick (1935) have shown that grasses, including *Agropyron repens*, can act as alternative hosts. Volunteer cereal plants
and winter cereals serve a similar role in bypassing the saprophytic stage. *O. graminis* may form perithecia which in turn produce ascospores; these are normally dispersed in the autumn. Brooks (1965) found that these ascospores were only viable on exposed roots or on ground previously uncontaminated by the fungus. Although Padwick (1935) has shown that *Ophiobolus graminis* can produce perithecia on alternative hosts, it is the inoculum on roots that is the principal source of infection in cereals. In the absence of suitable hosts the persistence of take-all fungus in the soil is closely related to its ability to survive as a saprophyte. This ability is influenced by the activity of other soil microbes, some of them competitors with take-all.

Scott (1969) found that survival of take-all was influenced by its position relative to the soil; if infected straw was suspended above the soil surface, survival of take-all was prolonged. This was true to a lesser extent if the straw was laid on top of the soil rather than being completely buried. The rate of substrate decomposition was negligible in the suspended straw but relatively rapid for the buried straw. This demonstrated that treatment of infected straw may influence survival of the pathogen. Soil microbes exert a direct influence on the survival of *O. graminis*. Actinomycete isolates have been identified which are antagonistic to *O. graminis* (Cox, 1963). Lester and Shipton (1967) suggested that the reduced incidence of
take-all in the fifth successive cereal crop resulted from the development of a soil microflora antagonistic to \textit{O. graminis}. If inoculum is added to rotationally managed soil and soil in which successive cereal crops have been grown, a higher proportion of seedlings develop take-all on the rotationally managed soil. Shipton (1967) reviewed several instances in which incidence of take-all was reduced as a result of several years of continuous cereals. Work at Rothamsted (Slope & Cox, 1964; Cox, 1965; Cox, 1966; Etheridge & Slope, 1967) has revealed several examples of this phenomenon now known as take-all 'decline'.

The soil environment influences the activity of soil microbes, including \textit{O. graminis}, the principal factors being the availability of suitable substrates, soil temperature, aeration and moisture content. Fellows (1941) compared the survival of \textit{O. graminis} using temperature, soil compaction and moisture as variables and found that pathogen survival was enhanced in cool compact and dry conditions. Garrett (1936) identified some of the conditions favouring parasitic spread of \textit{O. graminis} as being warm, loose soil and high pH. Because \textit{O. graminis} is largely restricted to the surface of its host it tends to be vulnerable to changes in soil environment, hence assessment of take-all early in the growing season indicates its incidence rather than its potential effect on the crop.

Fellows and Ficke (1934) demonstrated in pots that
O. graminis not only reduced crop growth but it could also be fatal. More recently, Slope (1967) derived a direct arithmetical relationship between crop yield and incidence of take-all at the late-flowering/milky growth stage (Feekes scale 10.5-11) such that grain yield was reduced by 0.9% for each 1% increase in straws infected with O. graminis. Cunningham (1967) demonstrated that yields of wheat and barley were reduced if take-all inoculum was added to field plots.

Type of tillage implement, depth of tillage and time of tillage affect the physical spread and saprophytic survival of O. graminis (Sewell & Melchers, 1924; Scott, 1969). Brooks and Dawson (1968) and Hood (1965) have found that development of take-all was retarded in the absence of tillage.

Fertility level influences O. graminis in several ways; additional fertiliser stimulates root growth and may increase the probability of roots coming into contact with inoculum. Shipton (1967) found that crop resistance to O. graminis was stronger in the presence of applied nitrogen. Garrett (1936) found that plant survival was increased by applied nitrogen. Incidence of take-all was drastically reduced following heavy applications of nitrogen fertiliser, consequently differences in incidence due to other factors were much smaller if nitrogen was applied (Slope & Etheridge, 1967). In addition to increasing the extent of the root system, fertilisers also increase the availability of nutrients, thus reducing the
need for an efficient root system. Nitrogen also affects the survival of take-all in its saprophytic stage. Scott (1969) has suggested that additional nitrogen induces hyphal extension with the result that fresh substrate is exploited and survival thereby prolonged. Additional nitrogen also alters the C:N ratio and consequently the activity of the soil microbes, thus the actual effect of added nitrogen depends on availability of adequate substrate for both *O. graminis* and the microbes.

The influence of rotation on *O. graminis* has been studied at Rothamsted (Slope, 1967). Grain yields and incidence of take-all have been compared in successive crops of barley following break crops of oats and beans. The first crop after the break had only 5% of its plants moderately or seriously infected compared with 52% for the third crop after the break (Slope & Etheridge, 1967). In a comparison of rotational and continuous cereal growing Etheridge and Slope (1967) found that *O. graminis* was more prevalent in the second and third successive wheat crops after oats than in a wheat crop in its eighth successive year.

The object of the present study was to measure the effect of the tillage systems on the occurrence and severity of take-all. A review of previous work indicated that assay techniques based on growing plants on soil samples were unsatisfactory (Hornby, 1969a, b). The majority of field trials have involved assessment of lesions on the roots, stems or plants. Criteria in
common use are the percentage of plants or stems with *O. graminis* lesions on the roots or the characteristic collar on the stems. Cox and Slope (1963) differentiate between incidence of the disease (percentage of plants infected) and its severity (amount of infected root per infected plant). The former was measured by counting the number of plants in a known sample that exhibited *O. graminis* lesions on the roots. Severity was measured either by recording the number of infected roots or the percentage of the root system infected per plant. The former severity method was used at an early growth stage, soon after the crop had started tillering. This produced a measure of the inoculum potential within the soil. The later severity assessment was used at the late-flowering or milky crop stage of growth as a measure of the development of take-all within the crop. Cunningham (1967) adopted similar measures in his 'added-inoculum' work.

7.2 Experimental

For the purposes of take-all assessment the methods advised by Slope (1968) were adopted. The sampling periods were:

1968 24/28 June and 22/23 August
1969 23/25 June and 31 July/4 August
1970 28 June/2 July and 23/26 July

At each sampling period five randomly allocated samples, each one foot of drill, were dug up carefully so as to include as much root as possible. Surplus soil was
removed by gentle shaking, the sample was rolled into a thin canvas strip. With the exception of the August 1968 material, the samples were assessed within 24 hours. The August 1968 material was hung up to dry and assessed at a later date. Processing of samples consisted of soaking each in water to loosen the soil, separating out the individual plants and counting both the number of plants and tillers. After careful washing of the roots, samples were laid out in white trays with the roots floating in water. The number of plants with obvious take-all lesions were counted in each sample; this together with the total number of plants per sample provided a measure of disease incidence $(\frac{\text{No. of plants with } O. \text{ graminis lesions}}{\text{No. of plants in sample}})$. 

At the early sampling date severity of infection was assessed by counting the number of infected roots and dividing it by the number of infected plants:

$(\frac{\text{No. of roots with } O. \text{ graminis lesions}}{\text{No. of infected plants in sample}})$; at the later sampling, severity was scored as follows:

- No obvious visible infection: 0
- Seminals and 1 or 2 crown roots infected: 1
- Crown roots moderately infected: 2
- All roots totally infected: 3

The two severity assessments were measures of the extent of the fungus on the root systems of infected plants; the later assessment was presented as $(\frac{\text{The sum of severity scores}}{\text{No. of infected plants in sample}})$. To provide continuity all assessments were done by the same person.
Results (Tables 59-61)

Throughout the three years shallow and chisel ploughing resulted in a higher incidence of take-all than the other two treatments; this trend was evident at the first sampling date and consistently thereafter. Compared with the other tilled treatments, the inoculum potential in spring 1970 was enhanced by deep ploughing in the previous year. Incidence on the chisel ploughed treatment was prone to large changes both during the summer and winter.

Between 1968 and 1970 _O. graminis_ inoculum potential increased on the tilled treatments. Incidence of take-all in the crop at Feekes stage 10.5+ (Large, 1954) was dependent on season; in 1970 it was less than in 1969.

The severity assessment was limited to infected plants only. On each sampling occasion a number of subplots exhibited no sign of take-all, consequently subplot data were bulked before analysis. Replicates were excluded if any of their mainplots failed to exhibit take-all. Tillage treatments had little effect on the development of _O. graminis_ on infected plants, apart from a tendency in 1969 and 1970 for disease development to be reduced with deep ploughing.

There was a consistent inverse relationship between the rate of nitrogen applied and the incidence of take-all. At the high rates of applied nitrogen _O. graminis_ was inhibited to such an extent that tillage differences were reduced; this interaction was significant ($P<0.05$) in August 1969 and June 1970. Within a season the rate at
which incidence of take-all increased was limited by application of nitrogen.

7.3 **Discussion**

The major results of this assessment demonstrated that incidence of take-all in barley continuously grown for three years did not increase with direct drilling, and that its increase was most rapid with shallow and chisel ploughing. Differences in tillage effects were expected as this experiment included depths of tillage and different implements, both factors known to affect take-all (Scott, 1969; Sewell & Melchers, 1924). Sewell and Melchers examined fifteen tillage treatments representing different dates and depths of ploughing; although take-all levels varied with treatments there were no clear trends. Scott (1969) found that take-all 'whiteheads' were reduced by early rotavation, or late ploughing in comparison with early ploughing. He suggested that early ploughing increased saprophytic survival. Brooks and Dawson (1968), Hood *et al.* (1964), Hood (1965) and Jeater (1966) found that incidence of take-all was reduced on direct drilled plots in comparison with tilled ones. Their results agree with the general findings of this trial.

Differences in incidence resulted from the effect of tillage and nitrogen treatment on the active spread of the fungus between living roots, passive spread by implements or changes in the conditions affecting saprophytic survival.

The tillage treatments of this trial consisted of an
undisturbed treatment, both deep and shallow inversion treatments and a dragging, loosening treatment. Soil movement resulting from such treatments varied both horizontally and vertically. In the absence of cereals or alternative hosts take-all is immobile (Padwick, 1935). Garrett (1936) has shown that take-all infection results from physical contact between an infected root and a clean one, consequently active spread is a slow process depending on the probability of this contact occurring. However, if infective propagules are spread uniformly through the medium the chances of clear roots being infected is increased. This spreading action is achieved by horizontal soil movement.

Chisel ploughing results in horizontal soil movement, conventional ploughing is less effective as it does not have the same stirring action; secondary cultivations also stir the soil. The spread of take-all assumed to result from ploughing is consistent with the incidence results for chisel and shallow ploughing but not for deep ploughing. Chisel ploughing leaves more stubble exposed than shallow ploughing; this may prolong saprophytic survival in a way analogous to Scott's experiment with straw suspended above soil (1969).

The hypothesis that stirring a soil with a given infective propagule population results in more uniform spread and higher potential incidence of take-all assumes that there is no loss of infective material. With chisel ploughing and secondary cultivations there is
comparatively little vertical soil movement, but with deep ploughing, and to a lesser extent with shallow ploughing, the vertical movement is considerable. Although Fellows and Ficke (1934) found that pathogenic vigour within the top 20 cm of soil was unaffected by the depth from which inoculum was taken, injury to plants decreased the further seeds were planted from the source of inoculum. Although Scott (1969) has shown that deep burial of take-all may enhance its survival, it does also reduce the probability of roots coming into contact with infective propagules. As the root system becomes less extensive at depth and there is a beneficial delay between plant establishment and seminal roots reaching the deeply buried inoculum, deep ploughing may result in temporary or permanent non-availability of part of the inoculum potential. Towards the end of the three year period there was evidence that incidence on the deep ploughed treatment was increasing relative to its performance in previous years. In 1970 the incidence was higher than on the direct drilled treatment and by August it was almost as high as on the other two tilled treatments. Scott (1969) has shown that deep ploughing can prolong survival of *O. graminis* and Garrett (1938) found that survival was enhanced in water-logged conditions, hence this rise in incidence on the deep ploughed treatment may have resulted from previously buried propagules being ploughed up still in a viable state.
The early sampling has two components, it is partly a measure of saprophytic survival through the winter and partly a measure of passive spread by tillage implements. The comparative wetness of the direct drilled treatment in winter, together with its high apparent organic matter content in the top 12 cm may have prolonged survival of the pathogen, but they did not increase its infectivity in spring. Slope (1967) and Lester and Shipton (1967) have shown that inoculum survival was poor if added to a site previously contaminated with take-all. There appeared to be a soil factor on Broadbalk and other continuous cereal sites that inhibited\textit{O. graminis}. One of the subsidiary effects of tillage may be the movement of take-all away from the rhizosphere to a locus in which these inhibiting influences or competitors are less virulent. Consequently survival of the pathogen may be encouraged by tillage.

Added nitrogen decreased incidence of take-all. But additional nitrogen, by increasing the extent of the root system, in theory increases the probability of clean roots coming into contact with infective propagules, thus additional nitrogen should increase incidence. This did not happen so either additional nitrogen enhanced plant resistance to infection or it decreased the inoculum potential. There was no direct evidence to support either explanation, but the latter one may operate if the additional nitrogen produces a more favourable C:N ratio and thereby stimulates microbial activity. Since straw
has a high C:N ratio additional nitrogen may stimulate this activity to the detriment of *O. graminis* and its substrate.

Although the mechanisms remain unidentified, direct drilling in this and other trials has resulted in low incidences of take-all; however, the large differences experienced at the low nitrogen rates are of little practical importance due to the very high rates generally applied by continuous cereal growers. Within the context of this experiment there were high incidences of take-all at the low nitrogen levels. If Slope and Etheridge's relationship (1967) of a 0.9% loss of grain yield for each 1% of plants with take-all is accepted in principle, the loss in yield on some treatments was large (up to 46.5% for chisel ploughing at N1 in 1969).

However, the severity of take-all on plants was generally less than that experienced by Slope (1968), possibly due to the much shorter growing period of the Edinburgh crop. Since Slope's association between take-all and yield is based on incidence of plant infection, no account is taken of differences in severity of that infection. Due to the relatively low severity of infection at Edinburgh, the effect of take-all on grain yield was considered to be less than a 0.9% reduction per 1% plants infected.
SECTION 8

COUCHGRASS INCIDENCE

8.1 Review

Experience of continuous barley growing, particularly in conjunction with direct drilling (Jeater, 1966; Hood, 1965) has revealed serious grass weed problems.

Direct competition between weed and cereal has been proven. Evans (1966) has shown that a mean increase in grain yield arose from control of couchgrass on 39 NAAS trials. Erskine (1970) demonstrated an inverse relationship between the level of couch infestation and grain yield; a reduction in couch shoots per square foot from 22.3 to 9.4 was accompanied by an increase in grain yield from 16.6 cwt/acre to 23.8 cwt/acre for spring barley. In an indoor experiment Williams (1969) measured the effect on wheat of competition with couch. The competitive ability of couch was minimised by early sowing of the cereal. Compared with absence of couch, late sowing of cereal resulted in a reduction of ears produced per cereal plant of up to 52%; this was accompanied by a 10% reduction both in 1000 grain weight and the number of grains per ear. This experiment was conducted with adequate light and water, whereas under field conditions, where intensities of couch reach 200 shoots per square foot (Erskine, 1970), both these factors, as well as nutrients can further limit cereal production.

In addition to direct competition with the crop,
Hughes (1966) reported a number of subsidiary detrimental effects resulting from the presence of couch. Apart from reducing speed of harvesting operations, couch increases the cost of grain conditioning and cleaning. *Ophiobolus graminis*, a foot-rot fungus on cereals, can survive on couch in the absence of its cereal host. Hughes (1966) also reported that cereal root eelworm and foliar diseases benefited from the presence of couch.

The growth of couch has been studied by Cussans (1968a, b), Palmer (1958), Sagar (1960) and Wareing (1964). In spring the basal lateral buds produce both tillers and new rhizomes. During the spring and summer the rhizomes elongate and produce lateral branches; in autumn the rhizome terminal buds become erect and form primary aerial shoots, the other buds remaining dormant unless disturbed by chemical or physical means. The following year the primary aerial shoots develop into mature plants generating a further set of rhizomes and tillers in the spring.

The problem presented in this work resulted from the intention to measure the couch infestation, initially low and sporadic in occurrence, on 128 plots without disrupting the other requirements of the trial. The usual methods of assessment include digging up rhizomes from beneath a square foot quadrat (Ramand, 1969; Waterson et al., 1964), washing, drying and weighing them or else measuring the occurrence of shoots (Lawson, 1962; Lowe & Bucholtz, 1951; Ramand, 1969). Although Evans (1966)
has questioned the reliability of equating couch measures on stubble with competitive ability in spring, it has often been impracticable to assess couch during the growing season either by digging up rhizomes or by counting shoots.

In the South Road experiment the number of visible flowering heads were counted in August. This measure represents that proportion of the total shoot population that produces ears, it disregards the 'blind' vegetative shoots mentioned by Palmer (1958). Furthermore, this method disregards those flowering shoots shorter than the crop; however, Cussans (1968a) has shown that couch reacts to competition such that its height is similar to that of its competitor. In addition to the flowering head count, a post-harvest assessment was also made. Variation in couch population was so high that it was impracticable to dig up sufficient quadrats and measure the couch accurately. The shoot assessment had to be rapid as it coincided with a period of shoot production. After several abortive attempts with quadrats of different sizes and frequencies, a method of visual assessment was adopted that combined a large sample area with an estimate of the actual area covered by couch in the sample.

8.2 Experimental

In August 1967, 1968 and 1970, the number of couch flowering heads were counted on each subplot.
The vegetative post-harvest assessment excluded the chisel ploughed treatment in 1967 as this treatment had already been imposed, likewise in 1969 the direct drilled treatment was excluded. The centre two feet of the yield area (Fig. 6) was marked with string for the full length of the subplot; this provided a sampling area 2 ft by 78 ft. The ground occupied by couch within this area was visually assessed in units of 0.1 square feet as the operator walked slowly down the 2 foot wide strip.

Results

The large number of flowering heads visible among the ripening crop was ample evidence that couch spread rapidly in the absence of cultivations. Shallow burial of the rhizomes was better than no tillage but better control was generally obtained by deep ploughing. Chisel ploughing depressed the flowering heads of couch to the same extent as deep ploughing.

Results from the vegetative shoot counts were similar to the flowering shoots in that in 1968 and 1970 the incidence of couch on the direct drilled plots was particularly high despite attempts to remove couch on this treatment both in 1969 and 1970. Of the tilled treatments the differences between them were small though deep ploughing consistently controlled couch spread better than the other treatments.

The flowering head data demonstrated that a small application of applied nitrogen increased the number of visible flowering heads. Comparison with the vegetative
assessment demonstrated that the nitrogen effect if present was negative.

Since the aim of this work was to record the incidence of couch and not necessarily the effect of the tillage systems on the couch, various actions were taken to limit its spread. These actions varied between the tilled and untilled treatments. The following action was taken: in May 1969 an attempt was made to fork out some of the couch rhizomes on the direct drilled plots. In 1970 rhizomes of couch were picked off the tilled plots after each of the two seed-bed harrowings. Prior to emergence in 1970 the direct drilled plots received spot dressing with paraquat on any visible couch shoots; during May each of the direct drilled plots was twice checked and any visible shoots removed. Because of this between year effects are not strictly comparable.

8.3 Discussion

Jeater (1966) found that paraquat did not control couch rhizomes. The South Road experiment, and others at Edinburgh, agree with his findings that couch is a serious problem if direct drilling is practised, especially in conjunction with continuous cereals. The ploughing results also agreed with previous work (Vengris, 1962; Dvornik & Vymetal, 1964). Control of couch by chisel ploughing was intermediate in effect and highly variable. However, chisel ploughing tends to be practised in the drier areas of Britain where harvest is early, and
the weather after harvest is generally good enough to encourage growth of couch after the first stubble cultivation. This was not the case on the South Road trial as harvests and removal of straw were comparatively late and they were followed by vegetative couch assessment. There was no evidence that the early first chisel ploughing in 1969 was more efficient than the later ones of 1967 and 1968.

Nitrogen application tended to reduce the incidence of vegetative couch present post-harvest, although it increased the number of flowering heads in August. The close connection between rate of nitrogen application and plant height renders the flowering head method of assessment a somewhat doubtful measure in the presence of different nitrogen rates. The decline in couch shoots post-harvest with added nitrogen may reflect the competitive stress resulting from the improved crop growth. Although nitrogen is beneficial to couch spread its influence on the growing crop appears to have more than balanced its positive effect on spread of couch.

A comparison of the two methods of assessment demonstrated that although not necessarily comparable in respect of nitrogen treatments the general conclusions to be drawn from the tillage effects were similar; however, the flowering shoot counts tended to give better differentiation between tilled treatments. The flowering shoot count was based on the development of basal lateral buds in spring to produce plants and tillers, whereas the
post-harvest assessment determined the extent of rhizome development during the growing season. It appeared that the production of plants and tillers was more susceptible to tillage differences than the rhizome development during the growing season.

In general the couch population was low; however, on the direct drilled treatment it did appear to be a competitor of serious potential. Of the tilled treatments deep ploughing was the most effective means of controlling the spread of couch.
GENERAL DISCUSSION

In common with other trials (Hood, 1964; Hood, Jameson & Cotterell, 1964; Hood, Sharp, Hall & Cotterell, 1964; Jeater, 1966; Wellings, 1968) direct drilling on South Road reduced cereal grain yields at low rates of applied nitrogen. The reduction in grain yield with direct drilling (Newbould et al., 1970b) was preceded by reductions in shoot yield (29% on 21 May and 14% two weeks before harvest). Finney and McIlvenny (1970) measured the grain yield, grain weight, grain number per ear and shoot yield of a winter wheat crop; tillage differences were not statistically significant due to lack of replication but certain trends were suggested. Direct drilling reduced grain yield if no nitrogen was applied but increased it if 100 kg N./ha were applied. Although grain number per ear was the dominant yield component in winter wheat (Finney & McIlvenny, 1970), Hood, Jameson and Cotterell (1964), Jeater (1966) and Wellings (1968) have shown that grain yield response to direct drilling is similar for both winter wheat and spring barley.

Differences in ear population on South Road resulted from tillage affecting both tiller production and survival; both are dependent on the soil's chemical and physical state, and the intensity of plant competition. As plant establishment tended to be similar for all tillage treatments, initial tiller production was affected by the
influence of tillage on the soil. The effect of take-all early in the season is slight and its incidence was smallest on the tillage treatment that produced fewest tillers. Tiller survival was similar for direct drilling, shallow and chisel ploughing and was consistently smaller with deep ploughing. As incidence of both couch and take-all was relatively small with deep ploughing, the reduced survival was due to other factors such as excessive tillering; possibly the soil conditions that promoted early growth with deep ploughing were unable to support such a dense tiller population. There was evidence of a permanent growth restriction with direct drilling as its small tiller population exhibited the same survival as the shallow and chisel ploughed treatments.

Russell (1966) suggested that direct drilling reduced nitrification and created a nitrogen deficit that might amount to 50 kg N./ha. Organic matter was seen to accumulate in the top few centimetres of soil under the South Road direct drilled treatment. Accumulation was measured at Jealott's Hill (Tomlinson & Piper, 1968). During, Robinson and Cross (1963) concluded that mineralisation of organic matter was a major factor affected by tillage. Roots and stubble are decomposed by microbes to form humus, carbon dioxide and nitrogen derivatives. If organic matter is added to a soil, the microbial population increases. But the C:N ratio of straw may exceed 90:1 and the microbe ratio is generally between 4:1 and 9:1, consequently the addition of straw to soil
usually results in the absorption of soil nitrate by the microbes to form protein. As their substrate is oxidised the microbe population declines thereby releasing nitrogen derivatives which can be oxidised in the soil to nitrate. As some of the released nitrogen was formerly incorporated in the straw and roots, nitrification of decomposed organic matter may increase soil nitrate levels. Both organic matter decomposition and mineralisation are oxidation processes, so tillage, by aerating the soil, increases the rate of both reactions. The microbes operate at soil temperatures above 2-5°C, and between field capacity and wilting point (Buckman & Brady, 1964; Russell, 1961).

During, Robinson and Cross (1963) measured soil nitrate levels in connection with different tillage systems. In the absence of tillage there was a temporary depression in soil nitrate level at the time of drilling, but seven weeks later nitrate levels were the same for the untilled and ploughed soils. Nitrification was retarded in the absence of the aerating effect of tillage. On South Road there was evidence of two conditions with direct drilling that may limit mineralisation. The air-filled porosity at crop emergence was consistently reduced by direct drilling and soil/stubble contact on this treatment was delayed until the plots were drilled and rolled. After drilling the stubble quickly disintegrated.

There was evidence that reductions in crop growth
after direct drilling may result from nitrogen deficiency. If the direct drilled crop received extra nitrogen its yield of shoots and grain were similar to the tilled treatment yields. An analysis of the nitrogen content in the shoots in June 1970 demonstrated a reduced percentage with direct drilling, but in 1968 and 1969 sampling, at a later growth stage, indicated that nitrogen percentage was largest with direct drilling. In 1970, compared with the tilled treatments, direct drilling reduced yield of nitrogen in the shoots more in July than at harvest; although the nitrogen deficit on the direct drilled treatment probably resulted from an early, but temporary, difference in availability, its effect on nitrogen yield was permanent.

Ploughing in 1969 was followed by several weeks of soil temperatures high enough for nitrification to occur. In previous years soil temperatures between the time of ploughing and drilling were seldom above 5°C for more than a few days. Although ploughing in 1967 and 1968 aerated the soil, established soil/stubble contact and probably increased the rate of organic matter decomposition, soil temperatures between ploughing and drilling were too low for nitrification. Consequently differences between tilled and untilled treatments were most conspicuous in 1970. Temporary differences between deep and shallow ploughing may operate if deep ploughing requires less soil nitrate for organic matter decomposition. Deep burial of organic matter reduces its availability
for decomposition (Arthur Rickwood EHF, 1970) and hence the requirement for soil nitrate; therefore, in the period following drilling, more soil nitrate may be available on the deep ploughed treatment. With shallow ploughing, and probably chisel ploughing too, much of the organic matter is decomposed by the time the soil temperature is high enough for nitrification, thereafter nitrate is slowly released. It is probable that with direct drilling, soil nitrate is absorbed by the soil microbes shortly after drilling, so its release is delayed until the organic matter has been decomposed and the nitrogen derivatives oxidised back to nitrate.

In addition to nitrogen effects tillage resulted in physical restrictions on root growth. The shallow root system developed in response to direct drilling (Finney & McIlvenny, 1970; Newbould et al., 1970b) was similar to the root system produced by Goss and Walter (1969) with reduced pore size. As the compactive effect of direct drilling was larger on South Road, the reduction in pore size was more drastic and it was accompanied by a reduction in total length of root in zones of high bulk density: a reduction in root length was experienced by Aubertin and Kardos (1965) if pore size was very small. In zones of high density there were examples of thickened roots symptomatic of mechanical impedance (Eavis, 1965).

At high nitrogen levels there was little evidence that an increase in root length was beneficial to shoot growth. Shallow ploughing was the highest yielding
treatment but its root response to applied nitrogen was generally the smallest. Early in the growing season the heavy shoot growth with deep ploughing coincided with an extensive deep root system. Whether this was due to soil nitrate being more available with deep ploughing, or to the reduction in soil bulk density between 24 and 36 cm, or a combination of the two, is not known. Later in the season length of root system below 36 cm was the same for all tillage treatments so small differences in the 24-36 cm horizon became less important.

Apart from altering the soil's physical and chemical state, tillage influences the development or control of take-all and couchgrass. If the Rothamsted relationship (Slope & Etheridge, 1967) between incidence of take-all and reduction in grain yield is applied to the South Road results, the relative performance of treatments is changed as shown below.

### Actual grain yield (t/ha), mean of 3 years

<table>
<thead>
<tr>
<th></th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>2.38</td>
<td>3.56</td>
<td>3.93</td>
<td>4.32</td>
<td>3.55</td>
</tr>
<tr>
<td>S</td>
<td>2.37</td>
<td>3.65</td>
<td>4.24</td>
<td>4.48</td>
<td>3.68</td>
</tr>
<tr>
<td>C</td>
<td>2.01</td>
<td>3.42</td>
<td>4.15</td>
<td>4.29</td>
<td>3.47</td>
</tr>
<tr>
<td>M</td>
<td>1.77</td>
<td>3.00</td>
<td>3.87</td>
<td>4.41</td>
<td>3.26</td>
</tr>
<tr>
<td>Mean</td>
<td>2.13</td>
<td>3.41</td>
<td>4.05</td>
<td>4.38</td>
<td>3.49</td>
</tr>
</tbody>
</table>
Hypothetical yield in absence of take-all (t/ha), mean of 3 years

<table>
<thead>
<tr>
<th></th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>2.64</td>
<td>3.89</td>
<td>4.20</td>
<td>4.47</td>
<td>3.80</td>
</tr>
<tr>
<td>S</td>
<td>2.96</td>
<td>4.19</td>
<td>4.51</td>
<td>4.89</td>
<td>4.14</td>
</tr>
<tr>
<td>C</td>
<td>2.87</td>
<td>4.09</td>
<td>4.41</td>
<td>4.62</td>
<td>4.00</td>
</tr>
<tr>
<td>M</td>
<td>1.96</td>
<td>3.25</td>
<td>4.01</td>
<td>4.50</td>
<td>3.43</td>
</tr>
<tr>
<td>Mean</td>
<td>2.61</td>
<td>3.86</td>
<td>4.28</td>
<td>4.62</td>
<td>3.84</td>
</tr>
</tbody>
</table>

The appearance of take-all on plants was seldom severe on South Road, hence the expected grain yield reduction was probably less than that experienced by Slope and Etheridge (1967) at Rothamsted. Although the Rothamsted relationship may not be applicable to South Road results, it is probable that take-all adversely affected grain yield. If it is accepted that take-all is detrimental to grain yield then in the absence of take-all, the depression in grain yield, due to direct drilling, would be even greater than actually measured. Despite its large incidence of take-all, the shallow ploughed treatment yielded more grain than the deep ploughed treatment, so it appears that in the absence of take-all a real difference exists between these two treatments.

The incidence of couchgrass was relatively small on the tilled treatments. If couchgrass did reduce yield, the reduction was least on the deep ploughed treatment, consequently in the absence of couchgrass, yields with
shallow and chisel ploughing would increase relative to deep ploughing. Incidence of couchgrass was much larger on the direct drilled treatment at all nitrogen rates, yet grain yield reduction was 25% in the absence of applied nitrogen, compared with no reduction if 150 kg N./ha were applied. In 1968 several direct drilled plots in the East bank of replicates had very small infestations of couchgrass, yet their grain yields were reduced compared with the appropriate tilled plots. Therefore couchgrass infestation may have contributed to the reduction in yield on the direct drilled treatment but its effect was relatively small.

Although it is not known to what extent factors such as soil physical conditions, nitrate availability and incidence of both take-all and couchgrass were implicated in the determination of grain yield on South Road, certain tentative conclusions may be drawn. Take-all was not implicated in the grain yield reduction on the direct drilled treatment, however it did appear to modify the relative performance of the tilled treatments. As incidence of couchgrass was much larger on the direct drilled treatment, at all rates of applied nitrogen, couchgrass was not a dominant factor affecting grain yield reduction on the direct drilled treatment. The dominant factors appeared to be soil nitrate availability, as delay in availability prejudices tillering rather than growth of individual tillers. Early availability, as suggested on the deep ploughed treatment, causes extensive
tillering but reduces tiller survival, and thus could account for differences between tilled treatments. Individual tiller growth did not compensate for the reduced stem density on the direct drilled treatment; it appeared that soil physical conditions associated with direct drilling restricted crop growth throughout the growing season.

Although responses to tillage systems have been recorded for the shoots and roots of a barley crop, couchgrass and take-all, the precise effect of incidence of couchgrass or take-all on yield is unresolved, so too is the requirement for roots. It is doubtful if the effect of take-all on grain yield can be reliably assessed on a trial containing as many variables as the South Road trial. Use of the added inoculum technique on land known to be free of take-all might establish a relationship between incidence and yield reduction. With couchgrass it would be practicable to relate the incidence measure used on South Road to the one used by Erskine (1970) in his work on couchgrass control. If couchgrass control without cultivation became technically possible, couchgrass could be eliminated on a random allocation of replicates, and its effect on grain yield examined experimentally on South Road. Future research could usefully concentrate on the availability and uptake of nitrogen. During, Robinson and Cross (1963) have measured soil nitrate levels on a tillage trial; they demonstrated that differences both exist and can be measured. A
combination of this work together with frequent shoot sampling for yield and nitrogen percentage should resolve one of the major suppositions arising from the present study. Further work on the effect of soil physical conditions on root growth, and the plant’s requirement for roots, is needed but it is doubtful if conclusive results can be obtained on a trial subject to as many variables as the South Road trial. Elimination of variables, such as take-all and couchgrass, would be possible on small plot trials; imposition of compacting treatments after drilling would eliminate variation due to drilling conditions (Prebble, 1970). Certain long term aspects of the South Road trial may alter the performance of the treatments. Take-all decline may operate at different rates on the tillage treatments, or it may start at different incidences; if grain yield is seriously affected by take-all then the relative performance of treatments may change in the future. The accumulation of organic matter on the direct drilled treatment may gradually lessen the detrimental effects of compaction, in particular it may increase the air-filled porosity.

Various conclusions can be drawn on the agricultural significance of the tillage treatments. Of the tilled treatments deep ploughing results in the best control of both couchgrass and take-all. In the short term its yield was less than with shallow ploughing; if the incidence of take-all or couchgrass increased, deep
ploughing might be the better treatment, especially as there was evidence of a plough pan developing on the shallow ploughed treatment. Early tillering on the deep ploughed treatment indicated that its early potential was not efficiently exploited in the later stages of vegetative growth; the causes require further investigation. The chisel ploughed treatment appeared to be unsatisfactory, but at the high nitrogen rates normally associated with continuous cereal growing, its incidence of take-all was considerably reduced and its grain yield on average was not much less than the deep ploughed yield. Furthermore the chisel ploughed treatment was imposed in conditions unsuited to its recommended use. Although direct drilling failed to control couchgrass, its grain yields at the high rates of applied nitrogen were as large as on the other treatments. On South Road the Fernhurst drill demonstrated that plant establishment was not adversely affected by the omission of cultivation, providing soil conditions were suitable. The cost of preparing the soil and drilling at current contractor's rates (Elrick, 1971) are £10.00 for deep ploughing, £6.50 for shallow ploughing and £7.50 for chisel ploughing. Scottish Agricultural Industries, the agents responsible for the Fernhurst drill, were not able to supply details of the comparable cost of direct drilling. However, if £2 is allocated to the cost of spraying with paraquat and a further £2 is allocated to the provision of extra nitrogen, a balance of £2.50 remains if hire of the drill, tractor and
operator is not to cost more than shallow ploughing. As farmers generally have equipment suited to conventional drilling, the variable costs incurred in ploughing and drilling are considerably less than those incurred by direct drilling. Economic use of direct drilling appears to be limited to those conditions in which its use may allow drilling to begin earlier in the year, or else prevent the use of heavy tractors working the land in unsatisfactory conditions prior to drilling. The large grain returns per kg applied nitrogen justified the application of at least 100 kg N./ha on the tilled treatments and 150 kg N./ha on the direct drilled treatment.
I wish to thank Professor N.F. Robertson and the ARC for providing the opportunity and facilities which enabled this thesis to be written. I am particularly indebted to Dr J.C. Holmes for his invaluable supervision and advice, and to Dr R.W. Lang and his assistants for help with the field and technical work. I am also grateful to Dr B.D. Soane and his colleagues for the easy liaison which existed between the crop and soil personnel and for providing me with useful soil data. Mr D. Paterson and his staff (ARC Statistics) have been most helpful in advising on the design of the experiment and the analysis of data. Dr J. Lennard kindly advised on the take-all work.
BIBLIOGRAPHY


## Appendix 1. Field operations.

<table>
<thead>
<tr>
<th>Operation</th>
<th>1967/68</th>
<th>1968/69</th>
<th>1969/70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep ploughing (single furrow digger plough)</td>
<td>21/22 November at 28-30 cm</td>
<td>26 November at 30-34 cm</td>
<td>5 October at 33-38 cm</td>
</tr>
<tr>
<td>Shallow ploughing</td>
<td>Ley plough, 20/21 November at 15-20 cm</td>
<td>General purpose plough at 15-20 cm</td>
<td>General purpose plough at 15-20 cm</td>
</tr>
<tr>
<td>Ohisel ploughing (9 tined superflow plough - 2 m wide)</td>
<td>19 October at 20 cm</td>
<td>29 October at 13-18 cm</td>
<td>24 September at 36 cm</td>
</tr>
<tr>
<td></td>
<td>9 November at 25-30 cm</td>
<td>12 December at 15-20 cm</td>
<td>7 October at 30 cm</td>
</tr>
<tr>
<td></td>
<td>23 November at 28 cm</td>
<td>13 March at 20 cm</td>
<td>4 November at 23 cm</td>
</tr>
<tr>
<td></td>
<td>28 December at 15-20 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct drilling (paraquat spraying)</td>
<td>23 November at 5 litres/ha</td>
<td>3 December at 5.5 litres/ha</td>
<td>5 September at 2 litres/ha</td>
</tr>
<tr>
<td>Fertiliser PK (Sisis spreader)</td>
<td>28/29 February, 67 kg/ha of both P₂O₅ &amp; K₂O</td>
<td>5/6 March, 67 kg/ha of both P₂O₅ &amp; K₂O</td>
<td>19 February, 78 kg/ha of both P₂O₅ &amp; K₂O</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary cultivation (D, S &amp; C plots)</td>
<td>15 April, 1 pass with Triple K and seeds harrows</td>
<td>30 March, 1 pass with Ballach harrow</td>
<td>26 March, 1 pass with Triple K harrow</td>
</tr>
<tr>
<td>Drilling</td>
<td>15 April M plots, 16 April D, S &amp; C plots, seed rate 173 kg/ha</td>
<td>29 March M plots, 1 April D, S &amp; C plots, seed rate 173 kg/ha</td>
<td>26 March, seed rate 220 kg/ha</td>
</tr>
<tr>
<td>Harrowing (D, S &amp; C)</td>
<td>16 April</td>
<td>1 April</td>
<td>26 March</td>
</tr>
<tr>
<td>Rolling (All)</td>
<td>28/9 April on replicates 5-8</td>
<td>28/30 April</td>
<td>1 May</td>
</tr>
<tr>
<td>Nitrogen treatments</td>
<td>14/6 May on replicates 1-4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spraying</td>
<td>7 June with MCPA/24DB at 7 litres/ha</td>
<td>5 June with MCPA/24DB at 7 litres/ha</td>
<td>28 May with Dicamba/Mecoprop/MCPA at 5.5 litres/ha</td>
</tr>
<tr>
<td>Combine-harvesting</td>
<td>16/17 September</td>
<td>27 August</td>
<td>1 September</td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>Plant establishment counts</td>
<td>7 May</td>
<td>23 May</td>
<td>2/4 May</td>
</tr>
<tr>
<td>Root growth and distribution</td>
<td>3/11 June</td>
<td>9/17 June</td>
<td>18/22 May</td>
</tr>
<tr>
<td>Root diameter</td>
<td>-</td>
<td>-</td>
<td>18/22 May</td>
</tr>
<tr>
<td>Dry matter yield of shoots</td>
<td>24/28 June</td>
<td>17/19 June</td>
<td>1/2 June</td>
</tr>
<tr>
<td>N, P, K content of shoots</td>
<td>24/28 June</td>
<td>17/19 June</td>
<td>1/2 June</td>
</tr>
<tr>
<td>Plants and tiller counts</td>
<td>24/28 June</td>
<td>23/25 June</td>
<td>28 June/2 July</td>
</tr>
<tr>
<td>Crop height</td>
<td>24/28 June</td>
<td>23/25 June</td>
<td>2 July</td>
</tr>
<tr>
<td>Take-all</td>
<td>24/28 June</td>
<td>23/25 June</td>
<td>28 June/2 July</td>
</tr>
<tr>
<td>Tiller counts</td>
<td>-</td>
<td>-</td>
<td>2/15 July</td>
</tr>
<tr>
<td>Root growth and diameter and distribution</td>
<td>-</td>
<td>14/22 July</td>
<td>-</td>
</tr>
<tr>
<td>Dry matter yield of shoots</td>
<td>-</td>
<td>28 July</td>
<td>15/16 July</td>
</tr>
<tr>
<td>N content</td>
<td>-</td>
<td>-</td>
<td>15/16 July</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>------------------</td>
<td>------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Take-all</td>
<td>22/23 Aug</td>
<td>31 July/4 Aug</td>
<td>23/26 July</td>
</tr>
<tr>
<td>Plant and tiller counts</td>
<td>22/23 Aug</td>
<td>31 July/4 Aug</td>
<td>23/26 July</td>
</tr>
<tr>
<td>Couch flowering heads</td>
<td>2 Aug</td>
<td>-</td>
<td>6 Aug</td>
</tr>
<tr>
<td>Crop height</td>
<td>16/19 Aug</td>
<td>8 Aug</td>
<td>6 Aug</td>
</tr>
<tr>
<td>Lodging</td>
<td>21 Aug</td>
<td>8 Aug</td>
<td>18 Aug</td>
</tr>
<tr>
<td>Root growth and distribution</td>
<td>24 July/1 Aug</td>
<td>11/15 Aug</td>
<td>27 July/1 Aug</td>
</tr>
<tr>
<td>Root diameter</td>
<td>-</td>
<td>-</td>
<td>27 July/1 Aug</td>
</tr>
<tr>
<td>Root length in horizon 36-54 cm</td>
<td>-</td>
<td>25 Aug</td>
<td>7 Aug</td>
</tr>
<tr>
<td>Ear and stem characteristics</td>
<td>28/29 Aug</td>
<td>29 Aug/1 Sept</td>
<td>18/21 Aug</td>
</tr>
<tr>
<td>Lodging</td>
<td>11 Sept</td>
<td>25 Aug</td>
<td>1 Sept</td>
</tr>
<tr>
<td>Degree of ripeness</td>
<td>6 Sept</td>
<td>-</td>
<td>3 Sept</td>
</tr>
<tr>
<td>N, P, K in shoots</td>
<td>-</td>
<td>-</td>
<td>3 Sept</td>
</tr>
<tr>
<td>Grain yield and characteristics</td>
<td>16/17 Sept</td>
<td>27 Aug</td>
<td>3 Sept</td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>Vertical distribution of pH, P - K in soil</td>
<td>-</td>
<td>1 Oct</td>
<td>-</td>
</tr>
</tbody>
</table>
Appendix 3. Meteorological Information.

The principal difference between the winters of 1967-1968, 1968-1969, 1969-1970 was the weather in February and March. This period was relatively wet in 1968 and exceptionally dry in 1969. But the soil conditions at drilling were sticky in 1969.

During May and June conditions were wet in 1968 and 1969, particularly in the former year, ground temperatures were low. May 1970 was exceptionally dry but no brighter than in the previous years.

1969 had the most bright sunshine at flowering and for several weeks thereafter; 1968 and 1970 were dull, wet and cool during this period.

In 1968 harvest was delayed by damp, overcast, weather. Harvest in 1969 and 1970 was relatively early; in the latter year it was preceded by a series of thunderstorms.
Rainfall (in.) - Total for month

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1966</td>
<td>1.90</td>
<td>3.25</td>
<td>1.46</td>
<td>1.94</td>
<td>1.88</td>
<td>4.66</td>
<td>2.16</td>
<td>7.79</td>
<td>2.38</td>
<td>2.27</td>
<td>3.24</td>
<td>3.22</td>
<td>36.15</td>
</tr>
<tr>
<td>1967</td>
<td>1.82</td>
<td>4.24</td>
<td>2.82</td>
<td>0.81</td>
<td>5.89</td>
<td>1.10</td>
<td>2.41</td>
<td>2.43</td>
<td>2.79</td>
<td>5.83</td>
<td>2.03</td>
<td>2.76</td>
<td>34.93</td>
</tr>
<tr>
<td>1968</td>
<td>2.47</td>
<td>2.51</td>
<td>3.02</td>
<td>2.14</td>
<td>6.02</td>
<td>1.23</td>
<td>5.53</td>
<td>2.43</td>
<td>4.78</td>
<td>4.68</td>
<td>3.09</td>
<td>1.56</td>
<td>39.46</td>
</tr>
<tr>
<td>1969</td>
<td>4.05</td>
<td>2.72</td>
<td>0.63</td>
<td>1.59</td>
<td>4.17</td>
<td>2.08</td>
<td>1.28</td>
<td>2.43</td>
<td>2.47</td>
<td>0.88</td>
<td>5.39</td>
<td>1.58</td>
<td>29.47</td>
</tr>
<tr>
<td>1970</td>
<td>2.33</td>
<td>3.05</td>
<td>1.45</td>
<td>2.06</td>
<td>0.95</td>
<td>1.84</td>
<td>3.44</td>
<td>2.57</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

4" soil temperature (°F) - Mean at 10.00 hrs

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>33.6</td>
<td>35.3</td>
<td>35.1</td>
<td>35.8</td>
<td>33.3</td>
</tr>
<tr>
<td>Feb</td>
<td>34.9</td>
<td>37.1</td>
<td>33.8</td>
<td>32.1</td>
<td>32.2</td>
</tr>
<tr>
<td>Mar</td>
<td>39.1</td>
<td>39.2</td>
<td>37.4</td>
<td>33.6</td>
<td>34.8</td>
</tr>
<tr>
<td>Apr</td>
<td>39.6</td>
<td>42.8</td>
<td>41.7</td>
<td>40.2</td>
<td>39.4</td>
</tr>
<tr>
<td>May</td>
<td>48.7</td>
<td>47.1</td>
<td>47.0</td>
<td>47.8</td>
<td>50.6</td>
</tr>
<tr>
<td>June</td>
<td>56.2</td>
<td>55.4</td>
<td>55.7</td>
<td>57.7</td>
<td>59.2</td>
</tr>
<tr>
<td>July</td>
<td>57.6</td>
<td>57.2</td>
<td>57.1</td>
<td>60.3</td>
<td>55.8</td>
</tr>
<tr>
<td>Aug</td>
<td>55.2</td>
<td>53.1</td>
<td>59.1</td>
<td>60.0</td>
<td>59.3</td>
</tr>
<tr>
<td>Sept</td>
<td>53.9</td>
<td>48.4</td>
<td>52.6</td>
<td>53.5</td>
<td>-</td>
</tr>
<tr>
<td>Oct</td>
<td>47.2</td>
<td>46.3</td>
<td>48.4</td>
<td>49.3</td>
<td>-</td>
</tr>
<tr>
<td>Nov</td>
<td>40.0</td>
<td>40.5</td>
<td>38.8</td>
<td>36.5</td>
<td>-</td>
</tr>
<tr>
<td>Dec</td>
<td>36.8</td>
<td>37.4</td>
<td>34.8</td>
<td>33.6</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Bright sunshine - Total hrs for month

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>24.1</td>
<td>44.6</td>
<td>35.5</td>
<td>36.6</td>
<td>32.7</td>
</tr>
<tr>
<td>Feb</td>
<td>28.9</td>
<td>74.7</td>
<td>67.6</td>
<td>65.2</td>
<td>113.4</td>
</tr>
<tr>
<td>Mar</td>
<td>126.6</td>
<td>131.0</td>
<td>99.6</td>
<td>69.3</td>
<td>123.1</td>
</tr>
<tr>
<td>Apr</td>
<td>109.7</td>
<td>137.9</td>
<td>144.0</td>
<td>147.3</td>
<td>112.3</td>
</tr>
<tr>
<td>May</td>
<td>204.5</td>
<td>124.3</td>
<td>117.3</td>
<td>91.0</td>
<td>111.9</td>
</tr>
<tr>
<td>June</td>
<td>96.7</td>
<td>208.0</td>
<td>180.4</td>
<td>198.2</td>
<td>171.1</td>
</tr>
<tr>
<td>July</td>
<td>179.6</td>
<td>175.7</td>
<td>104.8</td>
<td>179.6</td>
<td>105.2</td>
</tr>
<tr>
<td>Aug</td>
<td>95.3</td>
<td>141.6</td>
<td>157.5</td>
<td>166.3</td>
<td>139.5</td>
</tr>
<tr>
<td>Sept</td>
<td>110.8</td>
<td>103.1</td>
<td>84.0</td>
<td>109.6</td>
<td>-</td>
</tr>
<tr>
<td>Oct</td>
<td>80.9</td>
<td>108.0</td>
<td>77.0</td>
<td>97.7</td>
<td>-</td>
</tr>
<tr>
<td>Nov</td>
<td>38.2</td>
<td>59.7</td>
<td>36.1</td>
<td>55.6</td>
<td>-</td>
</tr>
<tr>
<td>Dec</td>
<td>29.0</td>
<td>45.0</td>
<td>22.6</td>
<td>19.3</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1021.6</td>
<td>887.6</td>
<td>961.3</td>
<td>-</td>
</tr>
</tbody>
</table>

Aim

To examine the effect of tillage on the vertical distribution of pH, P and K in the soil.

Method

After ploughing in November 1969 a limited number of plots were sampled to a depth of 20 cm using a screw auger. There were two replicates: replicate A consisted of bulked samples from the South Road replicates V and VI, replicate B was sampled on VII and VIII. Sampling was limited to direct drilled and shallow ploughed plots at all nitrogen levels. Each of the six auger samples per plot was equally divided into a top and bottom horizon, (both 10 cm.).

Results

For reference purposes the means of the three years were:

<table>
<thead>
<tr>
<th>Year</th>
<th>pH</th>
<th>P in ppm</th>
<th>K in ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1967</td>
<td>6.66</td>
<td>5.5</td>
<td>81</td>
</tr>
<tr>
<td>1968</td>
<td>6.60</td>
<td>6.8</td>
<td>86</td>
</tr>
<tr>
<td>1969</td>
<td>6.55</td>
<td>5.1</td>
<td>64</td>
</tr>
</tbody>
</table>

Distribution of pH

<table>
<thead>
<tr>
<th></th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>Upper horizon</th>
<th>Lower horizon</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct drilled</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.45</td>
<td>6.65</td>
<td>6.55 ±0.023</td>
</tr>
<tr>
<td>Shallow ploughed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.50</td>
<td>6.59</td>
<td>6.54</td>
</tr>
<tr>
<td>Upper horizon</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.48</td>
<td>6.63</td>
<td>6.55</td>
</tr>
<tr>
<td>Lower horizon</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.60</td>
<td>6.63</td>
<td>6.55</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.54 ±0.018</td>
<td>6.54 ±0.014</td>
<td>6.55</td>
</tr>
</tbody>
</table>
Apart from variation in pH with depth, there was also an interaction between depth and tillage such that ploughing reduced pH differentials.

**Distribution of P (ppm)**

<table>
<thead>
<tr>
<th></th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>Upper horizon</th>
<th>Lower horizon</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct drilled</td>
<td>5.62</td>
<td>5.12</td>
<td>4.13</td>
<td>4.13</td>
<td>3.56</td>
<td>5.94</td>
<td>4.75</td>
</tr>
<tr>
<td>Shallow ploughed</td>
<td>5.38</td>
<td>6.00</td>
<td>5.00</td>
<td>5.00</td>
<td>4.94</td>
<td>5.75</td>
<td>5.35 ± 0.463</td>
</tr>
<tr>
<td>Upper horizon</td>
<td>4.37</td>
<td>4.37</td>
<td>4.00</td>
<td>4.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower horizon</td>
<td>6.63</td>
<td>6.75</td>
<td>5.13</td>
<td>4.88</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>5.50</td>
<td>5.56</td>
<td>4.57</td>
<td>4.57</td>
<td>4.25</td>
<td>5.85</td>
<td>5.05 ± 0.330</td>
</tr>
</tbody>
</table>

The lower horizon was richer in phosphate, particularly on the direct drilled plots, and it was correspondingly poorer in the upper horizon. There was also a nitrogen effect such that at the higher rates of applied nitrogen less phosphate was available overall at the end of the season.
Distribution of available K (ppm)

<table>
<thead>
<tr>
<th></th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>Upper horizon</th>
<th>Lower horizon</th>
<th>Mean</th>
<th>± 4.11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct drilled</td>
<td>74</td>
<td>74</td>
<td>57</td>
<td>51</td>
<td>80</td>
<td>48</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Shallow ploughed</td>
<td>72</td>
<td>70</td>
<td>57</td>
<td>58</td>
<td>63</td>
<td>66</td>
<td>64</td>
<td>± 2.42</td>
</tr>
<tr>
<td>Upper horizon</td>
<td>80</td>
<td>81</td>
<td>63</td>
<td>63</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower horizon</td>
<td>66</td>
<td>63</td>
<td>51</td>
<td>47</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>73</td>
<td>72</td>
<td>57</td>
<td>55</td>
<td>72</td>
<td>57</td>
<td>64</td>
<td>± 1.10</td>
</tr>
</tbody>
</table>

T ns  TN ns  ± 3.44
N ** TH *** ± 1.60
H *** NH ns ± 2.20

The upper horizon was richer in potash than the lower one, tillage had no overall effect on levels of potash except that there was a clear interaction in which the level was particularly high in the upper horizon of the direct drilled treatment and correspondingly low in the lower horizon. On both tillage treatments an increase in rate of applied nitrogen reduced the available phosphate in both horizons.

Discussion

During the uniformity years the whole trial area received large applications of phosphate and potash. The data for autumn 1967 indicated that the nutrient levels and pH were adequate. Furthermore prior to drilling potassic supers were applied each year; this provided in 1968 and 1969, 29 kg/ha P and 56 kg/ha K,
and in 1970 34 kg/ha P and 65 kg/ha K. As a result of the tillage treatments there were very small changes in the removal of P and K in 1970, the largest differences being 1.8 kg/ha for P and 2.0 kg/ha for K; however, as shown above, tillage altered the vertical distribution of these nutrients. Despite this, the mean level for the top 20 cm of soil was the same for both nutrients on the two tillage treatments examined; furthermore this was the zone of soil that contained most of the root length. As the mean levels of the nutrients were similar for both treatments and also because of the subsequent overall dressing prior to drilling, it appeared that growth differences were not due to a change in the vertical distribution of the nutrients.

Nitrogen had an influence on the status of both P and K; this corresponded to its influence on the removal of nutrients in the harvested crop. The data presented in Tables 22 and 23 for removal of P and K were overestimates based on samples cut at ground level and lifted by hand rather than on that portion of the crop removed by combine-harvesting and baling. The increase in nutrient removed by hand harvest due to 150 kg/ha applied N was 9.9 kg/ha for P and 54.2 kg/ha for K. The removal at the N1 level for 1970 was 10 and 36 kg/ha respectively. The total removal of K at N4 exceeded the annual application but as this treatment had the highest potash content (Table 23) the short term effect of this imbalance was negligible.
One decision resulted from this work: the gradual fall in pH indicated that liming was required. The normal practice was a large application once every four or five years. The effect of such a dressing on direct drilled plots would have raised the pH to toxic levels, consequently a policy of small annual dressings was adopted.
Appendix 5. Mean number of Lumbricus adults and immatures in plot samples on 19 September 1969.

<table>
<thead>
<tr>
<th>Method</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep ploughing</td>
<td>34</td>
</tr>
<tr>
<td>Shallow ploughing</td>
<td>51</td>
</tr>
<tr>
<td>Chisel ploughing</td>
<td>25</td>
</tr>
<tr>
<td>Direct drilling</td>
<td>69</td>
</tr>
<tr>
<td>Se</td>
<td>± 10</td>
</tr>
</tbody>
</table>

This data was collected by Dr B. Gerard, Edinburgh School of Agriculture.