Crop Establishment in Relation to Soil Conditions and Cultivations

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Within certain limits growth during the early stages of crop development is not related to final yield, but after poor establishment heavy yields may not be attainable. Successful crop establishment does require that sufficient seeds germinate and seedlings emerge in environmental conditions that permit development to an extent that will ensure that the yield potential is not restricted. This is probably more important for spring sown cereals than those sown in autumn with a longer growing season.

In the narrowest sense, crop establishment may be considered as the number of seeds that germinate and from which seedlings emerge, but in the context of yield of cereals it is more purposeful to use a broader definition, and to consider also post-sowing conditions that influence the growth rate and development of those seedlings, since the seedbed conditions that can affect growth in the early stages can persist.

Several soil factors, including aeration, compaction, water supply and soil temperature can influence the rate of crop establishment. Obviously, excessively dry conditions can delay germination and emergence. This may also, for autumn sown crops, cause the seedlings to experience lower soil temperatures, which in turn affects rate of growth. While irrigation can be used to improve germination of cereals in dry conditions, tillage to eliminate weed competition and to modify soil structure, and drainage to improve aeration are the management practices most commonly used to modify soil conditions that can affect crop establishment. The effects of such practices may also persist throughout the growing season, and influence yield. Unsuitable soil conditions or time-consuming soil management practices can delay sowing, and these in turn may affect the rate of crop development and yield.

In Britain, during the last decade there has been a major change in the proportion of autumn sown cereals; in England and Wales it has increased from about a quarter to nearly three quarters. This has greatly increased the amount of land to be prepared during a short but critical period of about 6 weeks between harvesting and seeding early crops. Thus there is a very high premium on timeliness of operations.

In terms of farm output, and thus for the national yield, procedures that facilitate the planting of a large area closer to the optimum time are likely to be of the greatest practical importance. It is therefore, not sufficient merely to consider the impact of individual factors that affect establishment in a particular field but to integrate the consequences of different management practices into the whole farming system. In this paper much of the work refers to Western Europe, but reference is made to other areas where possible.

The pattern of root growth of cereals

The radicle primordium is already present in the seed, and in normal seed-bed conditions the radicle is clearly visible within 3-8 days after imbibition, depending on temperature. Up to 6 seminal roots /depending on the species of cereal/ normally emerge from the germinating seed. At about the four leaf stage of growth, the seminal roots can be about 30 cm in length, and already well-branched in suitable environmental conditions /Fig. 1/. At about this time nodal root axes begin to form and may eventually form a large part of the root system. On the main axis of wheat there are two roots per node, including the coleoptile node /KLEPPER et al., 1982/, and the total number of nodal roots is related to the number of tillers. Thus in widely spaced plants more than 100 nodal roots can form /SCHUURMAN and DE BOER, 1970/. Early sown winter cereals may be well tillered by December thus the relative proportions of the root system provided by seminal and nodal roots will depend on sowing date. The significance of the growth of nodal roots needs further examination.

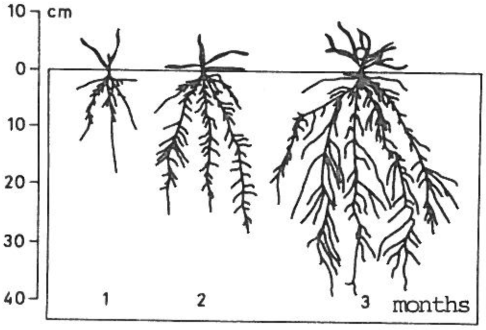

Fig. 1

Root and shoot systems of winter wheat 1, 2 and 3 months after sowing in mid-October /F. B. ELLIS and B. T. BARNES, ARC Letcombe Laboratory, unpublished/

The general pattern of root growth of wheat, barley and oats in well-drained soils without pronounced physical limitations has been described by WELBANK et al. /1974/ and by GREGORY et al. /1978/. In a temperate climate, as in Britain, the weight and depth of the root system increases steadily in the autumn and winter, with a mean extension rate of 5-6 mm day^{-1} /ELLIS and BARNES, 1980; GREGORY et al., 1978/ increasing to about 18 mm day^{-1} in the spring /GREGORY et al. 1978/ when soil temperatures are warmer. The latter rate is similar to the rate of the root elongation in laboratory conditions conducive to rapid growth rates /LUNGLEY, 1973/. Roots of winter wheat may reach 75 cm or even more by the beginning of April, and the maximum depth, normally reached by anthesis, can be 200 cm in winter wheat /GREGORY et al., 1978/, and in spring barley /KIRBY and RACKMAN, 1971/. Subsequently the total weight of the root system decreases, although root extension may continue in the deeper layers of the soil. However, most roots are concentrated in the upper 30 cm of the profile, though unfavourable soil structural conditions /see below/ can accentuate this situation, and in extreme conditions may prevent growth into the sub-soil.

Time of sowing and plant population

The yield potential of autumn and spring sown cereals is reduced by late sowing /MUNDY and McCLEAN, 1965; BELL and KIRBY, 1966; PROCTOR, 1974; REEVE and FAUSEY, 1974/, although seasonal weather variations do produce exceptions; for example WILLINGTON and BISCOE /1982/ found a yield loss of only 10% by sowing winter wheat in February rather than in September. Delayed sowing shortens the period of crop growth and development, but perhaps more importantly increases the risk of poor seedbed conditions /too wet or too dry/ later in the autumn or spring, so that uniform crop establishment is prevented.

In autumn, early sowing provides the crop with a warmer environment. Root growth is temperature dependent /Fig. 2/, so that early sowings provide an opportunity for more rapid root extension. Furthermore where winter cereals are sown before about mid-October, tillering is completed before the coolest part of the year /Fig. 3/, thereby maximising the yield potential.

The rate of germination, numbers of plants established and early plant growth can have more influence on spring sown crops than those sown in autumn. Winter crops have a longer period of growth increasing the likelihood that additional tiller survival can diminish or eliminate large differences in early growth, such that yield may be unaffected. Nevertheless in both periods late sowing can depress yields. Traditionally for winter cereals in Britain the target sowing date is about mid-October. However, where heavy yields /about 10 t ha^{-1}/ are expected earlier sowing is advantageous. In nationwide trials in 1981-1982 by the Ministry of Agriculture, Fisheries and Food, yield was increased by 10% from sowing in early to mid-September than in early to mid-October /J. BALDWIN, MAFF, Cambridge, personal communication/, and at Rothamsted Experimental Station in the multi-

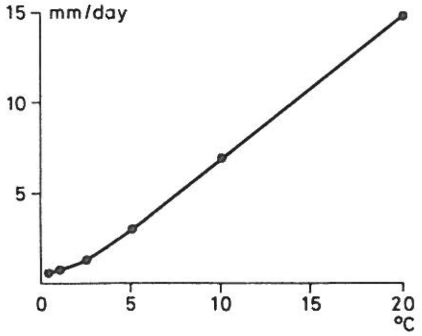

Fig. 2

Effect of temperature on rate of root elongation of cereals. Mean values for wheat, barley and rye, from VALOVICH and GRIF /1974/

factorial experiments sowing in mid-September rather than mid to late October was the most important variable after pest and disease control, increasing yield on average by 6%. Winter barley seems to be more adversely

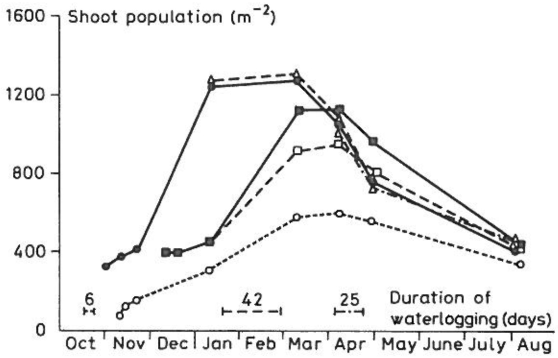

Fig. 3

Effects of sowing date and waterlogging on shoot populations of winter wheat. Treatments were: Sown October 26: • freely-drained, ○, ▲, △ waterlogging before emergence, in mid-winter and late winter, respectively; Sown November 29: ■ freely-drained, □ waterlogged in mid-winter /CANNELL et al., 1980/

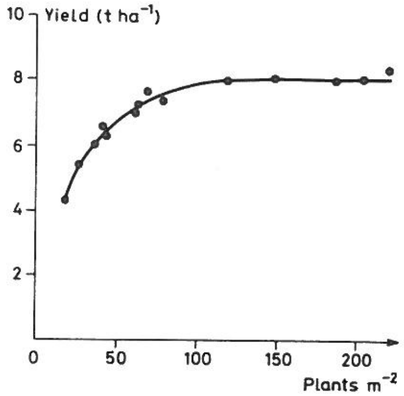

Fig. 4

Effect of plant population on yield of winter wheat /HUBBARD, K. R., ADAS, Cambridge, unpublished results/

affected by late sowing than winter wheat. The availability of fungicides and herbicides to minimise competitive factors is probably important in the tendency for early sowing in Britain.

Many experiments on plant population have been made, and as new varieties are introduced and management practices change the subject is reevaluated. However a consistent conclusion emerges that cereals can compensate for a wide range of plant populations /HOLLIDAY, 1960/ /Fig. 4/. Winter sown cereals can tolerate a wider range of populations than spring sown cereals; e.g. KIRBY /1969/ obtained the maximum yield for autumn sown barley with as few as 50 plants m^{-2}, but 200 plants m^{-2} were needed for spring sowings. The limiting plant population is likely to depend on the occurrence of other stresses /see below/.

In more arid environments the time of sowing has to be related to the pattern of rainfall; premature sowing may lead to severe moisture stress and seedling death.

Method of seeding

As yields have increased close attention has been given to all aspects of crop management, including the method of sowing. Most cereal crops in Britain are sown using drills with 11 to 20 cm row spacings with random distribution of seed along the row, often in combination with fertilizer /although on fertile soils where fertilizer has been applied over a long period there is no benefit from the latter practice /MINISTRY OF AGRICULTURE, FISHERIES AND FOOD, 1983/.

Evidence in the literature indicates that cereals may give heavier yields with square planting than from alternative arrangements /DONALD, 1963/. Square planting at the necessary close spacings is possible by hand, but precision drills that space plants at 2-5 cm intervals in rows 10 cm apart have been developed. However, such drills require firm level seedbeds, and the rate of work is often slower than with conventional drilling. In a summary of 32 comparisons of precision drilling at 10 cm row spacing with conventional drilling at 11-20 cm row spacing, but otherwise with identical management, GRAHAM and ELLIS /1980/ found that the average increase in yield of spring barley from precision drilling was 6.6% but 8.9% greater in experiments where the yield exceeded 5 t ha^{-1}. With 37 comparisons for winter wheat there was no difference between those seeding methods, even for yields from 7.5 to 10 t ha^{-1}, thus reflecting the ability of winter wheat to compensate for uneven sowing.

Broadcasting of seed should in theory give a more uniform spacing of seed if seedbed conditions are not cloddy. However, GRAHAM and ELLIS /1980/ found that the yield of spring barley was similar after broadcasting and conventional drilling onto cultivated soil /both followed by harrowing/, but sometimes differences up to 15% occurred, perhaps due to cloddy seedbeds and poor seed incorporation. In some experiments increasing the seed rate with broadcasting helped to ensure that sufficient seedlings established. For winter wheat the yield was 5.4% smaller after broadcasting than after drilling, but with adequate incorporation of seed after broadcasting similar yields of winter wheat can be achieved /TAYLOR et al., 1979/.

Thus in Britain, other things being equal, there seems to be little benefit from altering the method of seeding. In more arid areas, broadcasting seed is too risky, and wider row spacings are often used to minimise competition for water.

Effects of compaction

For roots and coleoptiles to elongate, the soil strength should not be excessive, a condition often associated with compact soil. Soil compaction increases the bulk density and, more importantly, eliminates many of the large diameter transmission pores that serve simultaneously as the major pathways for drainage of water, the exchange of gases, especially oxygen, between atmosphere and soil, and the unrestricted penetration of roots. In addition, few transmission pores are present where structure is interrupted by natural or induced pans, or in naturally structureless soils dominated by fine sand or silt-size particles that may also have surface crusts. All of these structures can be deleterious to plant establishment. When excessively wet they interfere with soil aeration; when drained, they may quickly harden to present a mechanical barrier to roots and emerging shoots. Changes in structure, especially through their effects on water content may have effects on soil temperature, but little information exists in relation to particular soil management practices. Small temperature differences integrated over many weeks could affect roots /Fig. 2/ and leaf canopy and ear development.

Mechanical impedance of roots and emerging seedlings arises when the soil pores are small, and the cohesive properties of the soil matrix resist deformation by the growing plant. Roots tend to follow lines of least resistance /fissures, worm channels/ through the soil matrix, but are unable to decrease their diameter to penetrate narrow rigid pores /WIERSUM, 1957/. The overall effect of impedance is to slow root penetration and shoot growth. Root systems remain shallow, and although there is no lesser ability of roots stunted by mechanical impedance to absorb nutrients /GOSS, 1977/, there is a greater dependence on fertilizer and on rainfall /rather than stored water/, because of the restricted depth of the roots; under extreme conditions crop failure can occur. Laboratory experiments show that relatively small stresses, around 0.5 bar /GOSS, 1977/ disproportionately hinder root and shoot extension, bearing in mind that the hydrostatic /turgor/ pressure that cells can generate is 10-20 bar.

The need for tillage

Tillage, in topsoil and sub-soil is the most obvious way to modify deleterious soil structure. However, uncertainty exists as to where tillage is needed for weed control, or for incorporation of crop residues rather than for alleviation of poor soil structure and consequent amelioration of crop growth. Where tillage is necessary, there is often doubt as to how much is needed. Clearly where the soil is badly rutted by wheel traffic, tillage is needed to remove the associated compaction, but in the context of ordinary soil conditions only a shallow depth of tillage may be required for cereals. We have to be careful in making generalisations, because the traditional method and depth of tillage can vary greatly between environments. For example in Italy there is a long tradition of deep tillage with mouldboard ploughing to 50 cm for winter wheat /and 75 cm for sugar beet and potatoes/, but in Australia the established tillage practice for wheat only involves soil disturbance to about 8 cm. Yet in both countries there is limited experimental evidence to support these practices, and current research is aimed at clarifying the situation.

There is a world-wide interest in the possibility of simplified tillage, brought about by the availability of a range of herbicides to control weeds. The reasons for this interest vary between climates, soil types and cropping systems, but include savings in the cost of fuel and machinery, shortage of labour, erosion control and conservation of soil water /especially important in tropical areas/, and more timely sowing, which in some regions also facilitates double cropping.

Timely tillage can alleviate soil compaction, but there is much evidence that repeated tillage can cause a deterioration of soil structure /LOW, 1972; GREENLAND, 1977/. Nevertheless not all soils are appropriate for direct drilling /zero tillage/. For example in the USA on well-drained soils, maize yields after zero tillage have equalled or exceeded yields after ploughing, but on poorly drained soils the reverse has occurred /GRIFFITH et al., 1973; VAN DOREN et al., 1976/.

In Britain, many clayey soils /which occupy 45% of the cereal growing area/ exhibit a degree of self-mulching in the upper 2-3 cm at the end of the summer, and this can provide ideal conditions for germination of winter cereals, provided that residues from the previous crop have been removed, preferably by burning /see below/. In two experiments on such soils during 7 years, direct drilling and shallow tillage gave similar or slightly heavier yields of winter cereals than after mouldboard ploughing, even in seasons favouring heavy yields /c 10 t ha^{-1}/ /CANNELL et al., 1982/. In these soils the pores are more continuous and less tortuous after direct drilling than after ploughing /BALL, 1981/ and infiltration of water and root elongation is aided by continuous transmission pores formed by cracking in summer, and by earthworms /GOSS et al., 1978/; root growth has been more rapid after direct drilling than ploughing except on the heavier soil in wet seasons /ELLIS and BARNES, 1980/. Even one ploughing on these soils can eliminate continuity of transmission pores /GOSS et al., 1983/.

In silty loam soils on loess in Germany, direct drilling has favoured deeper rooting and greater uptake of water by spring oats /EHLERS et al., 1980/1981/. In Britain, on a silt loam with comparatively low organic matter content, surface soil conditions were not favourable for plant establishment and yield after direct drilling in the early years of the experiment /ELLIS et al., 1982/. Recently, however, yields of winter cereals from the three treatments have been about equal, associated with more organic matter and stable aggregates in the upper 2.5 cm with direct drilling /DOUGLAS and GOSS, 1982; ELLIS et al., 1982/.

In several countries coarse-textured sandy soils have been amongst the least successful for direct drilling. This has been noted in Britain, and in Australia. On a loamy sand in Western Australia, in the fourth consecutive year of a long-term tillage experiment, after disc ploughing to 8 cm, soil strength was less than after direct drilling, root extension of wheat was faster and dry matter production greater, even from the early establishment stage. The direct-drilled crop could not compensate, and yield was about 20% greater in the crop sown after ploughing; over 5 years the yield was about 40% less after direct drilling than after ploughing /HAMBLIN and TENNANT, 1982/.

In a series of long-term experiments in eastern England, direct drilling on heavy soils has given consistently good yields of winter cereals, but not on light soils, nor for spring cereals /J. M. PROCTOR, ADAS, Cambridge, personal communication/. In more moist conditions in Scotland, even just broadcasting spring barley seed onto an uncultivated sandy loam soil, followed by very shallow tillage gave similar establishment and yields to conventional tillage /PIDGEON, 1980-1981/.

Assessment of soil suitability for direct drilling

Often there is only limited experimental evidence on the yield of crops with simplified tillage methods, and even less information on the effects of these methods on soil conditions, especially the physical conditions that may affect crop establishment, root growth and possibly yield.

Thus the possibility of making generalisations on the suitability of simplified tillage systems may be limited. It is not practicable to undertake field experiments on all soils, and thus the possibility of predicting where particular tillage methods may be appropriate, based on measured soil physical properties has much to commend it.

Topsoil properties which influence water transfer, aeration and root growth are likely to be important. For given environmental and management situations the physical characteristics of the surface layer when tillage has been omitted most probably depend on three aspects of soil behaviour: slaking by water /the stability of the structure to excess water/, compaction /the resistance to mechanical stress/, and fragmentation by swell/ /shrink activity and frost /the possible natural recovery from damage to the soil/.

In a recent investigation in the United Kingdom and France indices of the stability and shrinkage of soil aggregates and of compactability were prepared /STENGEL et al., 1983/. The three indices were ranked in high, intermediate or low groups, and the soils classified according to their ratings in these groups. The resulting classification of soil suitability for zero tillage agreed well with a previous one /CANNELL et al., 1978/ based on field experience and comparisons of crop yield of cereals in experiments on different soil types. The aggregate stability and shrinkage were positively related to organic-carbon and clay content, respectively. Soils with low clay contents and high proportions of sand or silt were identified as those likely to be problematic with zero tillage. In some cases the physical properties of the "problematic" soils were significantly improved by increased organic-carbon content in the surface 2-3 cm after repeated direct drilling.

Thus there is potential for classifying the suitability of soils for zero tillage using their physical properties, or mineral and organic compositions, or both. However, it would be inappropriate to extrapolate the conclusion from these limited investigations until such relationships have been more widely tested. Furthermore it would be important to establish the relationship between the chosen criteria and the consequences of soil structure in the field. In particular in areas where mulch is left on the surface of the soil, aggregate stability may be much less important than in places where residues are removed, so that the soil is exposed to raindrop impact. And where heavy tractors, combine harvesters and trailers are used, compactability may be much more important than in places where there is no wheel traffic.

Crop residues in relation to tillage

A prime reason for interest in zero tillage in many countries, e.g. in Brazil and USA, is lessening erosion. This is facilitated by the presence of crop residues on the soil surface, and hence the term "conservation tillage" is widely used /OSWALD, 1978/. However, where one crop closely follows another, residues that have not decomposed can mechanically interfere with drilling, especially when narrow rows are used, which tends to be the case in more humid areas producing heavy yields of straw /and grain/, and cause other adverse effects.

Substances from decomposing crop residues have been long considered as causes of poor growth and yield /COLLINSON and CONN, 1925/, and the effects have been recently reviewed /CANNELL and LYNCH, 1983/. Adverse effects of residues on subsequent crops are most evident if anaerobic conditions develop, and thus their significance in rice production has been much investigated /TANAKA and YOSHIDA, 1970/. The world-wide development and adoption of simplified and conservation tillage systems have brought the problems, as well as the benefits, associated with residues to prominence, because often these tillage systems involve leaving the residues on the soil surface or only shallowly incorporating them. When seed drills operate in such conditions, especially on heavy textured soils, when the residues decompose anaerobically seedling growth can be retarded. Such problems where cereals are grown with simplified or conservation tillage systems have been reported from Australia /KIMBER, 1967/, the United Kingdom /LYNCH, 1977/ and the United States /ELLIOTT et al., 1978/.

In wet autumns in the United Kingdom, establishment of winter cereals by direct drilling through residues from the preceding crop can result in poor plant establishment and lighter crop yields. Over a seven-year period the average yield of direct-drilled winter wheat and oats was 13% less in the presence of stubble than after burning all residues and 27% less in the presence of chopped straw and stubble; after shallow /7 cm/ tillage the corresponding figures were 8 and 20% respectively /Fig. 5/. These effects on yield followed the establishment of up to 50% fewer plants, that were less vigorous /Table 1/. Even after ploughing-in straw the yield of winter cereals was slightly less than after burning /OLIPHANT, 1982/. For all methods of tillage or with direct drilling the effects were more pronounced in wet conditions /CANNELL et al., 1982; OLIPHANT, 1982/.

In Britain, removal of straw and stubble, especially by burning, can have several benefits. These include killing weed seeds and fungal spores, and improved surface tilth conditions. Straw residues can impede the drill mechanism when direct drilling, giving uneven distribution of seeds, keep the topsoil wetter so that in wet seasons toxins from the straw may be produced, increase the number of slugs /D. GLENN, Long Ashton Research Station, personal communication/, and may lessen the effectiveness of residual herbicides /MOSS, 1979/. By the time spring crops are sown, the worst effects normally disappear, or are of little consequence.

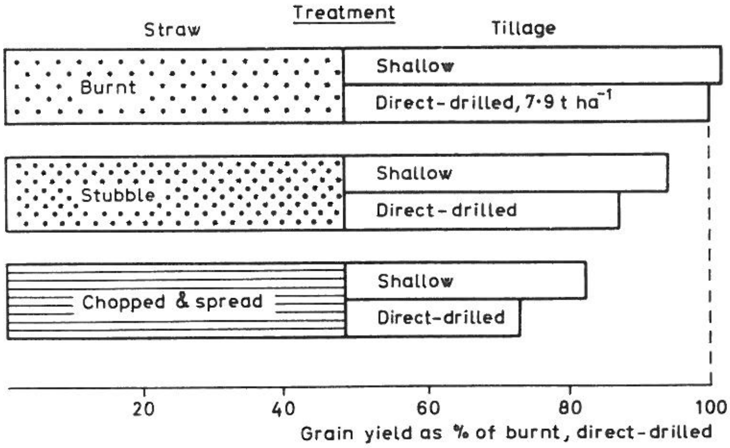

Fig. 5

Effect of crop residues and method tillage on yield of winter cereals on clay soils; mean results 1976-1982. /CANNELL et al., 1982 and unpublished results for 1982/

Table 1

Effect of methods of straw residue management on the number and size of winter wheat seedlings sown on September 29 after shallow tillage /7 cm/ or by direct drilling on a clay soil*

Straw treatment	Direct drilled		Shallow cultivated	
	No. of plants m^{-2}	Mean plant weight, g	No. of plants m^{-2}	Mean plant weight, g
November 9				
Burnt	336	0.034	295	0.034
Stubble only	205	0.027	241	0.026
Stubble with straw chopped and spread	177	0.024	194	0.023
April 19				
Burnt	243	0.96	285	0.84
Stubble only	169	0.74	207	0.70
Stubble with straw chopped and spread	133	0.52	193	0.63

* D. G. CHRISTIAN and D. P. MILLER, ARC Letcombe Laboratory, unpublished results.

The greater effects of straw in wet seasons are most likely due to slugs, and especially the formation of toxins when straw decomposes in anaerobic conditions. Laboratory studies with mixed populations of soil micro-organisms in liquid culture showed that phytotoxic concentrations of acetic acid rapidly accumulated from the anaerobic fermentation of wheat straw /LYNCH, 1977/. Although propionic, butyric, and hydrocinnamic acids also formed, and the adverse effects on growth increase with carbon chain length /LYNCH, 1980/, the concentrations were not phytotoxic. Acetic acid significantly restricted the extension of barley roots in concentrations of 15 mM at pH 6.5 and around 7 mM at pH 3.5. The greater effect at low pH is because the acid is associated, and therefore soluble in the lipid components of the root membrane. Residues from several species have all provided substrates for the formation of acetic acid in potentially growth-inhibitory concentrations /LYNCH, 1978; GUSSIN and LYNCH, 1982/. In experiments under controlled and field conditions in Australia, LOVETT and JESSOP /1982/ found that residues of a range of crop plants restricted germination, and growth of the coleoptile and seminal roots of wheat; residues of rape and some leguminous species had the greatest effects.

In the field the concentration of the acids produced in the soil is likely to vary partly with the distribution of the decaying residues /LYNCH et al., 198C/, since the effects on root and shoot growth vary depending on the proportion of the root system that is exposed and with the concentration of the acid /GUSSIN and LYNCH, 1982/; it is likely that roots will be sensitive to small concentrations /5 mM/ only if much of the root system becomes exposed. The concentration of acetic acid declines rapidly with increasing distance from the straw, halving over about 1.5 cm, since the acid does not diffuse far into the soil /LYNCH et al., 1980/.

Straw consists mainly of carbohydrates which decompose comparatively rapidly in soil, and are the likely source of acetic acid, and a smaller amount of lignin which decomposes slowly /HARPER and LYNCH, 1981/. The potential to form acetic acid thus diminishes after straw has been incorporated into soil, decreasing to quite low levels within about 6 weeks in the autumn /Fig. 6/, the rate depending on soil moisture and temperature.

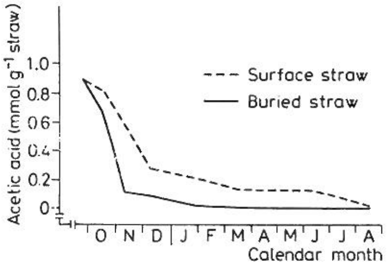

Fig. 6

The decline in potential for acetic acid production from decomposing wheat straw under field conditions /HARPER and LYNCH, 1981/

For autumn crops in the United Kingdom burning offers the cheapest and most effective way of avoiding the adverse effect of straw residues, provided it can be done without causing undesirable effects for the urban and rural population. However, in wet autumns burning may be only partially effective. Off-farm uses of straw are limited and, at least in the near future, incorporation of straw into the soil so that it decomposes in situ seems to be the best prospect for using excess straw that cannot be burnt. At present, however, we do not know the degree of "dilution" of straw with soil, and therefore the depth of tillage to minimise the problems. If the sowing had to be delayed until the straw had decomposed, there is a risk of lighter yields, especially on the clayey soils.

In drier environments or those with more extreme rainfall patterns many of the features of straw residues that prove disadvantageous in a humid moist climate provide the main justification for conservation tillage systems. In particular straw residues reduce the rate of run-off, lessening soil erosion /OSWALD, 1978/, and by increasing infiltration rates /TRIPLETT et al., 1968/ and reducing evaporation can increase the yields of maize on well-drained soils /VAN DOREN et al., 1976/. Although residues lower soil temperature, which can be disadvantageous for maize growing in North Central USA /GRIFFITH et al., 1973/, the cooler soil is an advantage in very warm areas, such as Nigeria /LAL, 1974/.

Wheel traffic in relation to tillage

The average weight of tractors and other farm machinery is increasing. In the U. K. from 1977 to 1982 the average weight of new tractors increased from about 3400 to 4200 kg, and the proportion of 2 and 4 wheel-drive tractors over 59 kW increased from 5 and 2% to 15 and 10% respectively; in 1972 the average size of new combine harvester was 6500 kg, but in 1982 it was 9700 kg /D. E. PATTERSON, National Institute of Agricultural Engineering, Silsoe, personal communication/. In the USA in 1976 the percentage of new tractors in the range 30-74 kW and 75 kW and over were 56 and 35, respectively. In 1981 the corresponding figures were 48 and 44%; in 1981 about 8% of new tractors were over 130 kW /INDUSTRY INVENTORIES, 1981/. These trends are probably increasing the risk of serious compaction by wheels in wet seasons, although tyre sizes tend to increase with increasing tractor weight. The worst risks are probably associated with specialist harvest machinery, such as pea viners and large sugarbeet harvesters, slurry tanks and lime-spreading trucks /the latter sometimes exceeding 20 t/. In regions where soils are generally dry and of high strength at cereal harvest, traffic may have little effect on soil structure, but in northern latitudes where the cereal harvest is later and the date of return to field capacity is earlier, harvesters may increase bulk density to depths of 15 to 30 cm in land ploughed in the previous spring /PIDGEON and SOANE, 1978/.

HAKANSSON /1982/ found that with the heaviest axle loads in current use, compaction may penetrate into the subsoil to 50 cm, and persist, even in areas with deep annual freezing; surprisingly in his work the effects of compaction on crop yield after four passes by a 26 t vehicle on ploughed land were only evident after the first year on sites with a high clay content. Seedbed traffic can also have adverse effects; in Scotland, on a sandy clay loam overlying a poorly drained clay loam, seedbed traffic drastically reduced air-filled porosity at seeding depth, plant establishment and yield /Table 2/, but without traffic there was satisfactory establishment and yield /CAMPBELL et al., 1982/.

Under continuous direct drilling the annual cycle of compaction and loosening of soil does not take place, and after about 2 years some soils may have sufficient strength to carry ordinary traffic without further compaction /PIDGEON and SOANE, 1978/. However if the particle size distribu-

Table 2

Effect of seedbed tractor wheel traffic on ploughed land on establishment and grain yield of winter barley /from CAMPBELL et al., 1982/

Number of wheel passes	Air-filled porosity at 3 cm /% w/w/	Number of plants m^{-2}	Grain yield /t ha^{-1}/
0	34.5	315	6.7
1r*	16.1	189	5.5
1	14.7	131	3.9
2	11.4	75	3.4
4	5.8	36	2.3
6	4.6	9	1.3
S.E.	3.6	26.7	1.5

* tyre inflation pressure at about half the minimum recommended values.

tion of the soil is such that the pores are too small for roots to enter, root growth will be restricted. Furthermore, when the soil is wet, rutting can still occur, and may prevent seed from being sown in suitable conditions. In such situations some remedial tillage will be essential, especially if the soil does not have swell/shrink characteristics.

We already have good evidence of the over-riding effect that wheel damage can have in direct drilling. In Nigeria, on an alfisol, where operations were carried out manually and there was no compaction, the mean grain yields of maize over 21 consecutive crops from 1971-1981 were 3.0 and 2.6 t ha^{-1} in direct-drilled and ploughed treatments, respectively /LAL, 1982/; this difference was associated with more earthworm activity and much greater infiltration rates into the direct-drilled land. However, when direct drilling and ploughing were used on a field scale, with conventional wheeled traffic for planting, spraying and harvesting, the relative yields were reversed, due to severe soil compaction /COUPER et al., 1979/. In Scotland, on a soil considered unsuitable for direct drilling, establishment after avoiding seedbed traffic was as good after direct drilling as with ploughing, but not where traffic occurred /D. J. CAMPBELL, Scottish Institute of Agricultural Engineering, personal communication/.

Thus it seems reasonable to predict that if wheels on machinery were modified to minimize soil compaction there could be considerable scope for reducing the amount of tillage /ELLIOTT, 1978/. However at present we lack critical information on the effects of wheel compaction on subsequent root penetration, growth and yield of cereal crops in conditions representative of normal farm practice. Further complications are seasonal variation in rainfall, leading to changes in soil moisture content and soil strength, which can greatly modify both the likelihood of compaction, and the extent to which compaction may influence subsequent crop growth. Also wheel compaction may induce waterlogging in the vicinity of germinating seeds, when they are most sensitive to oxygen shortage /see below/.

A comprehensive review of compaction by agricultural vehicles, and options for reducing compaction has recently been made by SOANE et al. /1980/1981 a and b, 1982/.

Deep loosening in relation to tillage

In earlier experiments in the USA /RANEY et al., 1955/ and in the U. K. /RUSSELL, 1956/, sub-soil loosening gave little benefit for cereal crops, and even now, after use of heavier equipment, yields are not always increased /SWAIN, 1975; UNGER et al., 1981/. In Britain there is renewed interest in the subject. This follows the results of a hand-digging experiment /McEWAN and JOHNSTON, 1979/ /where loosening the sub-soil increased the yields of the following four crops of winter wheat by 21% and spring barley by 11%/, and by the availability of a wider range of machinery to give more thorough sub-soil loosening. Several experiments with these machines have been in progress for up to 5 years, but there has been little benefit for winter cereals, but some for spring cereals on light soils. This may be because of the patterns of rainfall, so little water stress occurred, or because loosening was not needed on those soils. These treatments slow land preparation and are expensive, so we need to know where they are appropriate. They also need to be integrated into conventional tillage and field traffic systems, as they can render soil more prone to recompaction by subsequent traffic /STONE and ROWSE, 1982/.

Soil and plant aeration

Soil aeration can directly and indirectly affect the growth and function of roots and shoots, especially in the early stages of growth, and can affect the yield of cereals. Anaerobic conditions develop in soil when roots and soil organisms use oxygen for respiration faster than it can enter the soil by diffusion through interconnected air-filled pores. Oxygen diffuses in water about 10^4 times more slowly than in air, and so when soil becomes excessively wet or waterlogged, it effectively seals the soil from further gas exchange, and dissolved oxygen is consumed within a few days, depending on soil temperature and biomass. The oxygen in the topsoil can be used up in 4 to 6 days in autumn and spring in Britain, with the possibility of adverse effects of anaerobiosis on seedling establishment. However, it should be noted that the duration of near-anaerobic conditions is less than the period of waterlogging, especially in cooler periods of the year when oxygen consumption is slower.

Waterlogging just after germination but before the shoots have emerged /without the possibility of some oxygen transfer from the air to the roots via the shoot/ can greatly diminish the number of surviving seedlings as well as delay the emergence of those that do survive. This growth stage can coincide with the period of most rapid breakdown of crop residues, when phytotoxic substances may form in anaerobic soil conditions /see above/, so that seedlings may experience a combination of stresses. Winter wheat is very sensitive to small changes in the duration of pre-emergence waterlogging. At temperatures of about 10°C, few plants survived 6 days, and 10 days or more completely killed the crop at this stage /Fig. 7/. Pre-emergence waterlogging for less than 4 days in Britain would probably not depress yield of winter wheat, as with usual seed rates /about 400 m^{-2}/ an adequate number of plants /at least 150 m^{-2}/ would survive for normal growth and yield. However, if the duration of waterlogging exceeds 4 days the plant population is depressed below a number than can be compensated for by increased tillering and in other components, and yield may be less. For example in two experiments plant population were

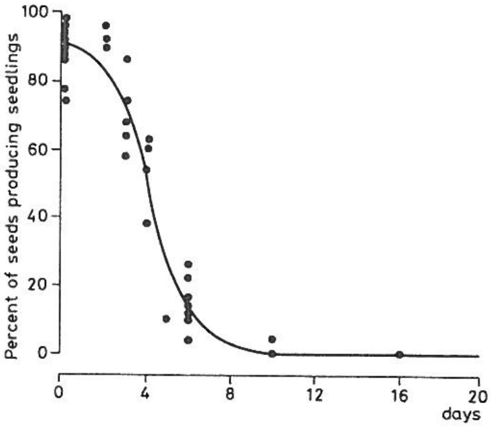

Fig. 7

Effect of pre-emergence waterlogging on establishment of winter wheat /CANNELL and BELFORD, 1982/. Horizontal axis: duration of waterlogging between germination and emergence, days reduced from around 350 m^{-2} in freely-drained control treatments to 11-42 m^{-2} after 6 days pre-emergence waterlogging, but more tillers survived to produce ears and the ears had more and heavier grains at harvest, so that the yield loss was only 17% /CANNELL et al., 1980/.

Laboratory studies have shown that calcium peroxide coated on cereal seeds has an antifungal action, neutralises phytotoxic acids that can occur in anaerobic soils, and can slowly evolve oxygen /LYNCH et al., 1981/. Such coatings have improved emergence of rice /YOSHIDA, 1981/, and in greenhouse experiments improved emergence of winter wheat from wet soils /SLADDIN and LYNCH, 1983/, but under ordinary outdoor conditions only improved emergence to a small extent both in freely-drained and waterlogged soil /THOMSON et al., 1983/. Calcium peroxide would seem to offer only a small benefit to establishment of wheat already treated with insecticide/fungicide dressings.

Pre-emergence waterlogging is most likely where perched water-tables occur in soils of low hydraulic conductivity, in soils that smear, especially with weakly-structured surface layers. The probability of pre-emergence waterlogging is greater with delayed sowing in the autumn, and can be worse with direct drilling than after ploughing.

In heavy soils, waterlogging may repeatedly occur at later stages of growth, since with low drainable porosity and slow conductivity, little precipitation is needed to saturate the soil profile. Thus effects of adverse establishment can be accentuated and poor drainage can considerably depress grain yield of winter cereals. In an experiment with winter wheat where 5 days pre-emergence waterlogging depressed yield by 4%, further waterlogging to the soil surface for 6 weeks in winter, during tillering, reduced yield by about 20% compared with a freely-drained control /CANNELL and BELFORD, 1982/. In undrained soils in regions prone to waterlogging, periods of surface waterlogging are accompanied by longer periods when the water-table is close to the soil surface, especially in winter. In undrained clay soils the winter water-table can fluctuate around 20 cm below the surface from December to April, the duration depending on the winter rainfall. Results from lysimeter experiments where the depth of water-table can be readily controlled show that the winter water-table should not exceed 50 cm except for short periods /CANNELL and BELFORD, 1982/. In the field this can be achieved by artificial drainage with mole-drains at 50-60 cm depth and about 2 m apart, draining into widely spaced gravel covered pipes /GOSS et al., 1981/, and grain yield of winter cereals can be up to about 25% greater than on undrained land /ARMSTRONG, 1978/. Also there can be indirect consequences associated with poor trafficability on land where drainage is inadequate that can affect both the current crop and possibly the one following. In drained soil, higher matric tensions are reached more rapidly and therefore soil strength can be greater. For clayey soils, STEINHARDT and TRAFFORD /1974/ and BAILEY /1979/ concluded that it is advisable to maintain the water-table below about 50 cm from the soil surface to minimise sinkage, compaction and structural damage. As a result, improved trafficability may make possible the earlier application of herbicides and fertilizer to winter cereals, and in the spring may facilitate earlier cultivation and sowing by increasing the number of work days /WIND and BUITENDIJK, 1979/.

Conclusion

Establishment of cereal crops needs to be considered in relation to the whole farming system; modelling techniques can help /AUDSLEY, 1981/. In Britain, where most harvesting is in August, an efficient system is critical because of the emphasis on autumn-sown crops. The progressive grower is aiming to sow winter barley and winter wheat in early to mid-September. The real issue is not whether differences in sowing date or tillage method have a marginal yield advantage, but whether or not the system of crop establishment makes it possible to sow a large area of crops in the autumn /as they typically out-yield spring crops by 20% or more/, before the risk of wet soil conditions begins to seriously affect field operations and early plant growth. This puts a high premium on tillage systems with shallow depths of working or fewer passes.

Although simplified tillage systems have work rates up to six times faster than traditional systems /PATTERSON et al., 1980/, they require that residues be removed, and that wheel damage should be minimised. Faster rates of land preparation can be achieved using larger, more powerful /and expensive/ tractors, sometimes fitted with dual wheels or low ground pressure tyres for seeding. Leading farmers are attempting to integrate their tillage operations with modular width equipment to match the spacings of "tramlines", typically 12m apart, from which seed is sometimes broadcast, and subsequent spraying and fertilizer applications are made /on up to 9 occasions/, using low ground pressure equipment when soils are wet. Such field traffic systems to minimise compaction can be complemented at harvest by tractors with dual wheels and grain trailers with more and/or larger wheels. However combine harvesters pose the major problem; fitting dual wheels can invalidate a manufacturers' warranty.

If there was a greater emphasis on prevention of soil damage and therefore of impedance to root growth, rather than curing it, as at present, it is likely that tillage could be greatly simplified, making early sowing much more easily attainable, and lessening the risk of other stresses such as pre-emergence waterlogging.

Summary

In this paper the effects of sowing dates, plant population, method of sowing and effects of different tillage systems on growth and yield of cereal crops are considered. Particular emphasis is given to effects of crop residues and wheel compaction that may interact with poor soil aeration when inappropriate methods of crop establishment are used. It is stressed that these factors must be considered in relation to the whole farming system, and not in isolation. Soil management systems that prevent rather than cure soil damage could facilitate economies in crop establishment by lessening the need for tillage.

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