EFFECTS OF DIRECT DRILLING OPENERS, SURFACE RESIDUE AND EARTHWORMS ON SEED AND SEEDLING PERFORMANCE IN A WET SOIL

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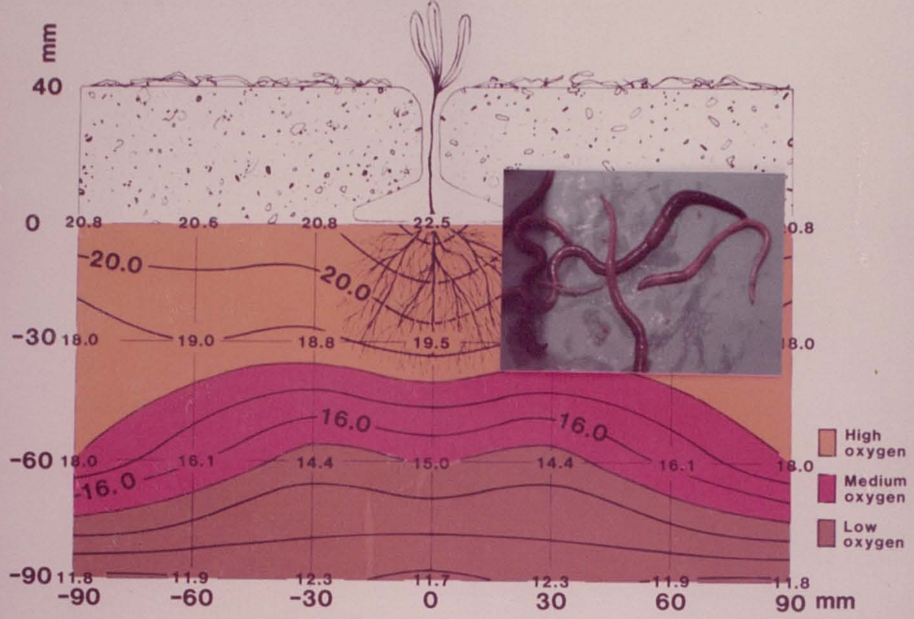

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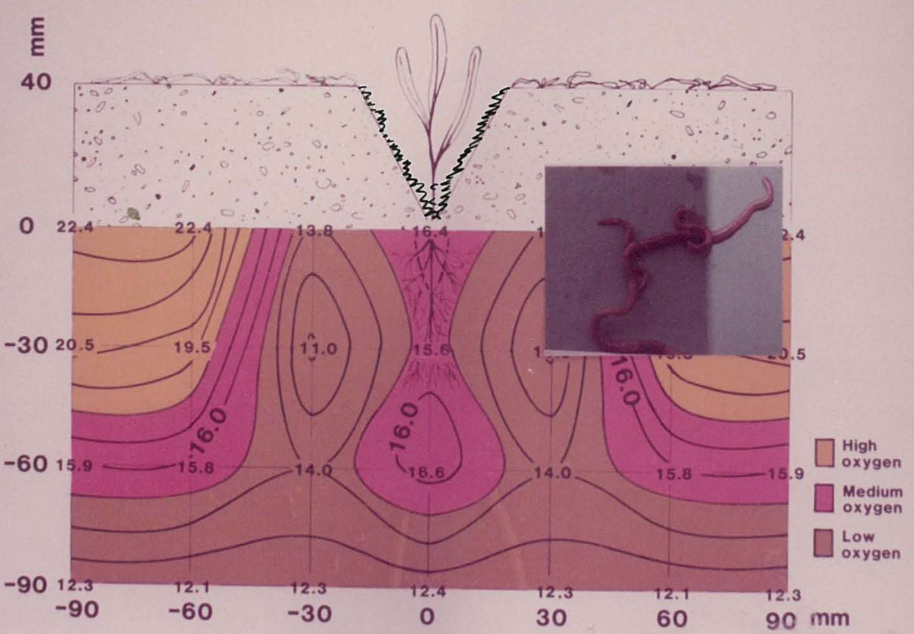
Oxygen diffusion rate (gm x 10^{-8}/cm^2/min): Winged opener in residue.



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Oxygen diffusion rate (gm x 10^{-8}/cm^2/min): Triple disc opener in residue.

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ABSTRACT

Stand establishment of crops by direct drilling is a function of seed germination and seedling emergence and their interactions with the soil physical micro-environment at or near the seed soil interface which itself is influenced by the design of direct drill openers. The main objectives of this project were to study the effects of opener types on seed germination and seedling emergence under continuously wet warm conditions. Experiments were conducted in the field under variable climatic conditions and in a laboratory under controlled conditions.

A field experiment showed that continuously wet soil conditions after drilling, resulted in significantly lower seedling emergence and root/shoot weights than non-irrigated conditions. Both field and laboratory experiments indicated that there were three strong influential variables; opener types, the presence or absence of surface residue, and the presence or absence of earthworms.

Five opener types and a surface broadcasting treatment were tested. Best results (in terms of barley seedling emergence) came from surface broadcasting on the untilled soil in all residue and earthworm conditions, and a winged (inverted "T" shaped groove) in the presence of both residue and earthworm conditions. A hoe opener ("U" shaped groove) in these latter conditions was marginally inferior to the winged opener in this respect. In the absence of both residue and earthworms there were few opener effects although the increased mechanical disturbance of a power-till opener (100 mm wide "U" shaped groove) gave the highest seedling emergence of all other "true" opener types in these conditions. Worst results involved a punch planter (discontinuous "U" shaped holes) and a triple disc opener ("V" shaped groove) in almost all conditions.

Crop residue conditions resulted in significantly higher numbers of emerged seedlings and greater root/shoot weights than no-residue conditions, under both simulated rain and temporary high water table conditions. Long residue (200 mm) showed a significantly larger number of emerged seedlings than short residue (40 mm) or bare soil (no-residue). Two opener types (winged and hoe) benefitted from the presence of crop residue, whereas with a triple disc opener the presence of crop residue was a disadvantage. This was because the function of the

winged opener kept the residue over the soil surface and the hoe opener swept it aside, whereas the triple disc opener pushed the residue down inside the groove and seed/residue contact appeared to have phytotoxic effects on seeds and seedlings. The performance of the triple disc opener groove was improved when residue was artificially removed from inside of the groove.

The narrow discontinuous "U" shaped holes created by a punch planter opener, the wide "U" shaped groove of a powered power-till opener and a surface broadcasting treatment did not appear to be influenced by the presence or absence of crop residue. Because precipitation was artificially regulated in these experiments, the latter technique was felt to be of limited practical importance, for untilled soils, because of the uncertainty of natural weather conditions following seeding in the field and the otherwise poor potential for seed/soil contact.

In the presence of residue there were higher oxygen diffusion rates (ODR) and lower soil bulk densities, together with increased earthworm populations and activity around the groove profiles of the winged, hoe, power-till and punch planter openers than under no-residue conditions. With the triple disc opener grooves, this trend was reversed, possibly because of compaction and smearing created by this opener.

The presence or absence of earthworms had a marked effect on seed/seedling performance. In the absence of earthworms the contrasting crop residue conditions and opener types had little or no effect on seedling emergence and seed/soil environment were in fact adversely affected by the absence of earthworms. The compacted and smeared groove of the triple disc opener showed lower numbers of earthworms around the groove profile than all other opener types under both residue and no-residue conditions. It was found that a high soil bulk density (1.4 g/cm^3), and to a lesser extent a heavy smear were detrimental to earthworm activity.

The absence of earthworms resulted in 7-9 fold lower cumulative infiltration around the groove profiles than where earthworms were present. Opener effects on infiltration strongly favoured the winged design in the presence of earthworms, but only when infiltration was measured to a depth of 100 mm.

It is therefore recommended that where surface residue and earthworms are present, use of a winged or perhaps hoe or power-till type opener is preferred in soil conditions likely to remain saturated during the germination and emergence phases. A power-till opener is preferred where residue or earthworms are absent. Use of triple disc or punch planter openers in any of these conditions is not recommended.

1. INTRODUCTION

Stand establishment of crops is markedly influenced by the efficacy of seed germination and seedling emergence. The total environment influencing germinating seeds is composed of physical, biological and chemical parameters. Within the broad range of non-limiting biological and chemical conditions, the stress imposed by physical factors in wet soil conditions may become the dominant force which might then limit seed germination and/or seedling emergence in the field. An understanding of soil physical factors and their inter-relationship with seed germination and seedling emergence is therefore fundamental to the precise functioning of seed drills, especially in relation to the design of furrow openers.

Seeds of field crops have been traditionally sown into conventionally tilled seed-beds. Considerable data are available concerning the characteristics of soil tillage profiles in such conventionally tilled seed-beds which have aimed at encouraging consistently optimum responses from seeds and seedlings during germination and emergence. In direct drilling (or no-tillage), because the technique is based on the avoidance of general seed-bed tillage (with or without herbicides), the seed is sown directly into the untilled soil. Most of the comprehensive work to date at Massey University, New Zealand has sought to characterise the micro-environments created by direct drilling openers in dry soils, and has centered on three opener types (winged, triple disc and hoe). Under wet soil conditions, little comparable data exist for untilled seed-beds. If the experience in dry soils is to be followed, extrapolation from tilled seed-beds might be (at best) unwise, and (at worst) distinctly misleading.

Phytotoxic effects of decomposing crop residues under the cool wet soil conditions in the United Kingdom have been described, but no interactions with opener types have been studied. Moreover, little information has been available regarding the comparative performance of opener types in the presence or absence of crop residues and/or earthworms under wet soil conditions. The objective ,therefore, of this study was to identify and investigate the salient physical and biological parameters which might be altered by the action of different direct drilling opener designs in wet soils, and in turn to study the effects that these might have on seed germination and seedling emergence of barley.

2. REVIEW OF LITERATURE

2.1 PHYSICAL, BIOLOGICAL AND CHEMICAL INFLUENCE OF CROP RESIDUES ON DIRECT DRILLING

2.1.1 Physical influence:

(a) Soil moisture:

The most frequently quoted determinant of evaporation and soil moisture content in no-tillage has been surface residue. Crop residues have been reported to reduce the evaporation of water from the soil surface and the lower evaporation rate from a mulch has allowed greater storage of water in the soil profile and availability to the crop during the growing season (Larson, 1970). Some authors have attempted to quantify these effects (Triplett et al, 1968; Anon, 1961). These authors found that soil with residue occupying 80 % ground cover sustained higher soil moisture contents than soil with "normal" residue (40 % ground cover). Even lower soil moisture contents were observed in these experiments in the absence of crop residue. However, Jones et al (1969) found no significant difference in water contents below 300 mm with or without surface mulch, but they were unable to explain the reason for this. These findings were confirmed by Lal (1978) under Nigerian conditions who found that tillage treatments (with and without mulch) had no significant effects on moisture storage capacity at 300 mm depth in soils with low moisture holding capacity.

In no-tillage situations, mulches, by definition, are confined to a surface covering. However, following normal tillage they may be left on the surface or incorporated in soils in many ways. Aldefer and Merkle (1943) observed that the moisture content beneath a surface mulch never fell below 20 % in any season in Pennsylvanian soils but he failed to produce comparable data for incorporated mulches. Others (Schneider, 1979; Stobe, 1980) considered standing stubble to constitute a mulch. They showed that tall stubble greatly increased moisture availability to plants, particularly in dry seasons. Further, under a no-tillage system trash provided an excellent medium on which snow mould could grow, according to Stobe (loc cit).

Crop residues are not only important on dry soils. In irrigated soils crop residues have had an influence on water-use-efficiency under no-tillage systems. For example, Allen et al (1975) found that wheat residue in irrigation furrows promoted a high rate of water advance which resulted in more uniform soil wetting. In these experiments the water-use-efficiency averaged 1.8 and 0.97 kg/m^3 respectively, for no-tillage and tillage experiments. They concluded that total water-use-efficiency could be attributed to the early season residue effect on slowing evaporation loss, and increased growth and yield in most years.

(b) Infiltration:

The infiltration rate of a soil has been defined by Richard and Wadleigh (1952) as when a soil, in a given condition at a given time, can absorb rain. It may also be defined as the maximum rate at which a soil will absorb water impounded on the surface at a shallow depth when adequate precautions are taken regarding border or fringe effects. Quantitatively, infiltration rate has been defined as the volume of water passing into the soil per unit of time. It has the dimensions of velocity. The term infiltration capacity of the soil was the same as infiltration rate, according to the Soil Science Society of America subcommittee on permeability and infiltration (Richard and Wadleigh (loc cit).

Mulching effects soil structure both directly and indirectly. Lal (1976) found that under Nigerian conditions crop residue minimized the direct impact of rain drops, there was minimal crustation and therefore, the initial pore space was maintained. Indirectly, mulching influenced the activity of microflora and fauna and hence soil structure. Other authors (Lal, loc cit; Perr and Bertrand, 1960) claimed that plant residues and the addition of microbial decomposition products of plant residues resulted in a marked increase in water stability of soil structure which increased the water infiltration rate of the soil. This work seemed to indicate that microbial by-products played an important role in increasing infiltraton rate of soils.

The amount of crop residue per unit area may affect bulk density and soil infiltrability both in initial run and wet run. For example, Triplett et al (1968) showed that infiltration at the end of one hour during both initial and wet runs with corn stover mulch (80% ground cover) exceeded other treatments (40% ground cover, no-till bare soil, ploughed bare). However, Aldefer and Merkle (1943) claimed that surface mulching was always better than incorporation of mulching material under no-till systems.

(c) Soil bulk density:

Bulk density is a weight per unit volume that indicates the amount of soil compaction and is inversely associated with the amount of porosity. Porosity is reduced by compaction which in turn reduces the size and volume of space between soil particles. Surface mulches effect earthworm activity and this biological activity, influences soil bulk density and porosity. For example, Lal (1976) reported that a 10 mm thick layer of dead crop residue on the surface of mulched tillage plots not only prevented crustation but stimulated biological activity and the bulk density of the surface soil horizon was generally low. Further he claimed that in temperate regions of western Nigeria a crop rotation under a no-till system lowered soil bulk density significantly (Lal,1978). Others (Triplett et al, 1968; Jones et al, 1969) claimed that soil with 80 % cover of crop residue lessened rain drop impact and lowered soil bulk density, while with 40 % residue cover or bare soil, bulk density was higher than with 80 % residue cover.

Less soil compaction due to tractor and implements, less resistance to penetration and lower bulk density, compared with conventional tillage have been claimed for direct drilled maize (Zea mays) crops by Rahman (1979) and Hoag et al (1980). No specific reasons for these claims were reported by these authors. However, Hoag et al (loc cit) felt that the extent and persistence of these changes would vary with soil type, the previous crop residues and the cropping system.

(d) Soil erosion and run-off:

Tillage practices without crop residue on the soil surface may result in high losses due to erosion and run-off, particularly on sloping soils. Lal (1978) observed that erosion increased exponentially with the increase of slope under high intensity storms. He felt that a continuously maintained cover of partially decomposed crop residue might decrease run-off and soil losses for soils of 1 to 15 % slope. However, under Nigerian conditions the mean water loss was 15 % lower in a no-till system compared with a conventional tillage system (Lal, 1976; Harrold et al, 1970). Larson (1970) observed that under high intensity rain only 1.0 t/ha soil was lost when covered with 3 t/ha of wheat straw. He commented that soil losses due to erosion and run-off were inversely proportional to the amount of crop residue on the soil surface.

Not only quantity, but quality of crop residues were important in reducing soil losses in a no-tillage system. Phillips (1973) reported that small grain straw and chaff provided excellent soil protection for a larger period of time than soybean residue. Further, corn stalks and grain sorghum stalks, when left standing after harvest, afforded considerable resistance to wind and water erosion, according to Phillips (loc cit). However, chopping stalks distributed them more uniformly and provided increased protection against the impact of rain and water erosion (Anon, 1961). The combination of taller soybean stubble, small grain stubble and the residues of both crops were found excellent in affording resistance against wind and water erosion (Phillips, loc cit). As a result authors have been in favour of proper crop rotation sequences to reduce soil losses and run-off (Cannel,1981).

(e) Soil temperature:

Crop residues influence not only soil moisture, infiltration, soil bulk density, soil erosion and run-off, but also soil temperature. In this respect, the amount of crop residue is of great importance. For example, the findings of Burrows and Larson (1962) showed that each tonne of crop residue applied reduced average soil temperature at 100 mm depth by about 1.0^{o} C. These findings were confirmed by Larson (1970), and Guard and Shaykewich (1980) on Manitoba soils. Harrapic (1980) felt that reduction in soil temperature due to crop residues on Manitoba soils were due to reflecting more solar energy with no-tillage (with residue) plots than with a tilled surface, and by acting as an insulating layer which inhibited heat movement into the soil. Schneider (1979) agreed with these findings with crop stubbles, and others (Stobe, 1980) also saw advantages in winter, because of increased soil temperatures. According to these authors better snow retention with stubbles meant warmer soil temperatures, and snow cover could be as deep as the height of the stubble. They claimed that soil temperature could be 10 ^{o}C warmer under no-tillage (with rape seed stubble) and never allow soil temperatures to reach -16 ^{o}C which could be a critical temperature for killing winter wheat. Pidgeon (1980) supported these findings on the sandy soils of Scotland with cereal stubbles.

Both crop residue and the nature of the crop canopy affected soil temperatures under Nigerian conditions, according to Lal (1976). He observed that close canopy crops such as cow-pea (Vigna sp) had lower maximum soil temperatures than maize. He further claimed that differences due to tillage treatments (no-tillage, conventional tillage) at 50 mm depth were as high as 11 ^{o}C for maize (Zea mays L.), 9 ^{o}C for soybean (Glycine max), and 6 ^{o}C for cow-pea, two weeks after planting. However, residue and the nature of the crop canopy had less effect at greater soil depths (Lal, 1978). He observed that under Nigerian conditions the differences in soil temperature (no-till, and till system) were 10 ^{o}C at the surface and 4 ^{o}C at 200 mm depth, and very little differences were found at a depth of 300 mm.

2.1.2 Biological influence:

(a) Seed germination and seedling growth:

Under cool or wet soil conditions crop residues might reduce soil temperatures with a resultant reduction in initial crop growth. Larson (1970) described that in Ohio mulched treatments reduced soil temperatures and corn seedling growth. Harrold et al (1970) commented that this initial growth reduction under mulched treatment conditions was due to a cooler, wetter and denser seed and root environment especially under a no-till system.

Under normal conditions the proper amount of crop residue has been found helpful in increasing plant height. In this respect, Triplett et al (1969) noted that plant height under no-tillage with "double" residue (80 % cover) was significantly higher than plant height with "single" residue (40 % cover) or without residue. These findings were similar to those reported earlier by the USDA (Anon, 1961). In these trials the plant heights in no-till (with residue) were almost double those in conventional tillage. These authors were unable to describe any particular reason for this effect.

(b) Crop yields:

Crop yield is influenced by the physical, biological and chemical properties of crop residues in no-tillage systems. Lal (1978) reported that the effect of mulching on crop yields was an integrated effect of innumerable factors and that it was difficult to attribute yield increments to any one variable. Despite this complex influence of crop residues Larson (1970) found that on a crusting silt-loam soil following corn sod with no residue cover, corn yields with no-tillage treatments were lower than ploughed plots, but yields with no- tillage with complete mulch cover were greater than the ploughed plots on the same soil. He further noted on Wooster soils that the advantage of no-tillage corn yields was greater following a fescue sod than corn, because the sod gave a better mulch cover.

The amount of mulch cover in no-tillage has been found to be a determinant in increasing some crop yields. Many authors have reported that about 50% mulch cover was necessary for no-tillage to equal conventional tillage corn yields (Larson, 1970; Harrold et al, 1970; Doren et al, 1973). In this respect, Triplett et al (1968) found that corn yields with 80 % residue cover were higher than 40 % residue cover or without residue. However, he claimed that during high rainfall periods the mulch cover had adverse effects on corn yields. This effect had been more severe on poorly drained soils. However, Doren et al (loc cit) suggested that growing corn under mulch tillage (stirring of the soil to a depth equivalent to the depth of the mould-board plough yet retaining all or most of the previous crop residues at the soil surface), would seem to be an important factor over ploughing or a no-tillage system. Others, (Triplett et al, 1973; Blevins et al, 1971) reported that with soils with low water holding capacity (such as sandy or silt loam soils) mulch under a no-tillage system gave better crop yields. Further, the standing residue of no-tillage had an advantage over shredded residue in plant growth and yields, according to Allen et al

(1975).

(c) Crop residue and earthworm activity:

There have been many reports in the literature of cultivation decreasing earthworm populations but there is also evidence that one or two light cultivations had little effect on earthworms and could favour earthworm activity and temporarily increase numbers (Hopp and Hopkins, 1946). Edwards and Lofty (1972), however, reported that cultivation over a number of years had tended to decrease earthworm populations. There was some evidence that this effect had been caused less by mechanical damage, or bringing the earthworms to the surface where they could be preyed upon by birds, than because of a gradual decrease of organic matter status in land that was continuously cultivated. Evidence in support of this had also been provided when the effects of mulching with the residue of the previous crop had been studied (Hopp and Hopkins, loc cit).

More recently with the advent of minimal cultivation and zero tillage or direct drilling, it has been shown that large populations of earthworms could build up even on regularly cropped land (Edwards and Lofty, 1975, 1982).

It has long been known that soils which contain organic matter or previous crop residues had large populations of earthworms (Edwards and Lofty, 1975), because the most important factor controlling the earthworm populations in arable land was the amount of organic matter that was available as food (Edwards and Lofty, 1972). They found that in a stubble-mulch farming system where crop residue was left on the surface and soil was worked underneath this layer, earthworm populations were three times higher than in ploughed plots. Further, they reported that Graff had pointed out in 1964 that mulching favoured the deposition of casts on the surface of arable land. These findings were confirmed by Lal (1976) under Nigerian conditions. He claimed to have counted $2400/m^2$ earthworm casts for no-tillage with crop residue, compared with less than $100/m^2$ for ploughed plots. Others concluded that the rate of earthworm cast production depended on the species, soil temperature, soil moisture and availability of organic matter and crop residues (Lal and Vleeschauwer, 1982).

The burning of straw in cereal fields after harvest has been increasingly common in the United Kingdom. Studies at Rothamstead since 1974 have shown that the deleterious effect of straw burning upon earthworms were due more to the removal of the straw which was a source of organic matter, than to any direct effect of burning (Edwards, 1981). Edwards (loc cit) concluded that removal or burning of straw or other crop residues had severe adverse effects on earthworm populations, particularly when the straw was burnt.

2.1.3 Chemical influence:

(a) Crop residues and plant nutrients:

Plant nutrients and chemical properties of soil are greatly affected by the decomposition of crop residues under no-tillage systems. Larson (1970) reported that plant nutrients were not a problem under a mulched no-tillage system for corn planting, as N applied to the soil surface moved through the profile with soil moisture. These findings were confirmed by Shear (1967) who claimed that on the silt loam soils of Virginia, N and P were higher under a no-tillage mulched system compared with ploughed treatments. However, other USDA experiments showed no difference of N, P and K contents of leaves with a grass mulch under no-tillage and a ploughed system (Anon, 1961).

Sch n eider (1979) noted that increasing stubble height increased available water and as a result nutrient uptake was increased. These results were supported by Toosey (1973) in the United Kindom. He felt that frequent failure of crops occurred because of omission of stubbles during direct drilling. Nevertheless, he suggested that up to 125 kg/ha N might be justified for stubble brassica drilled in July on fields that had grown cereals for several years.

The continuous cover crop residues retained in mulched tillage plots have helped maintain the ever dwindling organic matter content of the top soils at acceptable levels. In this respect, Lal (1976) claimed that under tropical soil conditions mulched tillage plots had higher concentrations of divalent cations on the exchange complex, more nitrate and nitrogen, and available P than ploughed treatments. He felt that crops which left more residue on the surface maintained the organic matter concentration at higher levels (e.g. maize), than those which had little or no residue (soybean). This indicated that the role of suitable crop residues was important under mulched treatments. These findings were supported by Joe and Lal (1979) who reported that no-tillage led to the stratification of soil pH in the 0-500 mm profile and crop residues in the system resulted in higher concentrations of C, N, P and exchangeable Ca, K than ploughed plots in the 0-100 mm layer. They commented that nutrient depletion in conventionally tilled plots was mainly due to accelerated soil erosion.

It has been reported , however, that during a normal rainy season irrigation might enhance leaching of fertilizer, and fertilizer requirements even under mulched tillage might be higher as a result. Lal (1978) reported that during a normal rainy season plants under unfertilized mulched tillage showed frequent symptoms of N and P deficiency. These results were supported by Syriffuddin and Zaudstra (1981) who claimed that "in rice fields because of puddling and flooding P was not sufficiently available to the corn plants sown in rice fields after harvest".

(b) Crop residues and toxicity:

Experiments in the United Kingdom have demonstrated that crop yields could be decreased if straw residues from the preceding crops were not removed, particularly when direct drilling in a wet autumn (Ellis and Lynch, 1977). Similar problems have been encountered in U.S.A. where straw was deliberately left on the soil surface to conserve moisture (stubble mulch) in the Mid-West (McCalla and Norstadt, 1974) or to prevent water erosion in the Pacific North West (Lynch et al,1980).

Several explanations for the harmful effects of straw have been put forward, such as mechanical difficulties in drilling, immobilization of nutrients (particularly N) and production of phytotoxins. Lynch (1977) claimed that when wheat straw was subjected to aerobic and anaerobic decomposition in a suspension of soil, the product of aerobic suspension stimulated the root extension of barley seedlings, whereas the anaerobic fermentation yielded products which inhibited growth. He found that acetic acid was the phytotoxin present in the greatest amount in these experiments. Ellis et al (1975) commented that a possible explanation for this was that toxic substances were produced by anaerobic microbial activity on the unburnt straw of the preceding crop which was incorporated with the seed during drilling.

Lynch (1978) conducted a series of experiments to explain the phenomenon of phytotoxicity under anaerobic conditions. He found that when acetic acid, which had accumulated in slurries of peat, loam and clay soils, was mixed with wheat straw the growth of roots of young barley was reduced. He felt that break-down of acetic acid was slow in flooded soils, and that maximum accumulation took place under these conditions. By contrast, aeration of the soil prevented its accumulation. Solutions in which straw had fermented, produced inhibitory effects on seed germination and the growth of seedlings in atmospheres containing between 3 and 21 % oxygen. More recent observations demonstrated that phytotoxic concentrations (10 mM) of acetic acid could accumulate in the water in contact with straw 24 hours after insertion into wet soil. In the field seedlings were affected mainly when their roots came into close contact with the decomposing straw (Lynch et al, 1980). In this respect, Cannel (pers.comm, 1982) suggested that incorporation of straw at the time of sowing should be avoided. He felt that early incorporation of straw could minimise the potential of toxin production during winter. He further pointed out that where the straw residues were mixed into the soil 3 weeks after harvest and 3 weeks before drilling (so that decomposition of straw had already started) the effects on subsequent crop yields were less, but still important. Lynch (1977) suggested dusting the seed with powdered chalk to "mitigate" phytotoxicity.

2.2. INFLUENCE OF EARTH-WORMS ON SOIL FERTILITY AND PLANT GROWTH

Earthworms influence soil structure in a number of ways. They are particularly important in the latter stages of soil formation and their main contributions are in the turn-over and mixing of the soil; the formation of the aggregates; improving soil aeration; porosity and drainage; and in the breakdown and incorporation of organic matter into the soil.

(a) Turn-over of soil:

Edwards and Lofty (1977) reported that large amounts of soil layers were brought to the surface and deposited as casts. The amount turned in this way differed greatly with habitat and geographical region, ranging from 2 to 250 tonnes per hectare. This was equivalent to bringing up layers of soil, between 1 mm and 50 mm thick, to the surface every year. In addition large amounts were deposited either as surface casts, or within burrows, so that soil turn-over was even greater. The type and placement of cast materials differed with the species. Typical of those which cast large amounts of soil on the surface were Allobophora Longa in Europe and Hyperodrilus africanus in Africa. Other species lined their burrows with cast material or at random in the upper soil layers. An active earthworm population produced a well broken down and mixed soil in the top 150 mm to 200 mm of the soil profile (Edwards, 1981). Allolobophora longa mixed the soil vertically compared to the lateral activity of Allolobophora caliginosa and Lumbricus rubellus (Springett, 1983).

(b) Formation of aggregates:

Aggregates consist of mineral granules linked together into larger and more stable particles. They can resist wetting, erosion and compaction and contribute considerably to a good soil structure. It has been considered that soil which has passed through the intestines of earthworms usually contain a higher proportion of aggregates than before ingestion (Hopp and Hopkins, 1946; Chadwick and Bradley, 1948). It was not known how earthworms produced these aggregates but there was evidence that the addition of organic matter to soil could increase the degree of aggregation (Dutt, 1948). It was possible that the association of organic matter with larger microbial populations was the main reason for the increased aggregate formation by earthworms in soils, according to Edwards, (1981). These findings have been supported by Stockdill (1959) in New Zealand , by Barley (1959) in Australian and by Lal (1976) in Nigeria. The latter, at least discussed work carried out under a no-tillage system.

(c) Soil aeration:

There have been many reports of increases in soil porosity and drainage due to earthworm activity (Hopp and Slater, 1948, 1949; Ehlers, 1975). Not only have soils with earthworms drained more freely, but also capillary water tended to be retained better and there have been reports of earthworm activity increasing the field capacity of the soils (Dixon and Peterson, 1971). Ehlers (loc cit) claimed that earthworm channels were more effective in transmitting water in untilled plots compared to tilled plots. He commented that earthworm channels might not have continuity on ploughed plots while on untilled plots the continuity of these channels was not disturbed. Further, soils with earthworm channels drained 4 to 10 times faster than soils without earthworms (Hopp and Slater,1949). Earthworms have increased the field capacity of some New Zealand soils compared with soils without earthworms; by as much as 17% (Stockdill, 1959).

However, little or no quantitive data are available on soil aeration status with and without earthworms, particularly in direct drilling systems when the soil is wet. Nevertheless, Barley (1959) observed that earthworm channels provided a path of gaseous excahnge from 200-500 mm in depth in the red brown wet soil of South Australia. He further observed, however, that the total cross sectional area of earthworm channels in the subsoil was too small to make a useful contribution to gas exchange by diffusion.

(d) Break down and incorporation of organic matter:

Many species of earthworms have been favoured by the presence of organic matter. Barley (1961) observed that dead leaf litter was removed rapidly from the soil surface and incorporated into the soil by the earthworms. Earthworms could consume and incorporate into the soil, cosiderable amounts of organic matter. Even soil inhibiting species could consume as much as 40 mg per gram of body weight per day. "Such movement of organic matter is particularly important in the natural habitat, particularly wood lands, in orchards and, also in agricultural soils that are under a zero or minimal tillage system. Their activity is also increasingly important in arable soils to which they have been added". (Edwards, 1981). These findings were supported by Edwards and Lofty (1982) who recommended that on arable land straw should not be removed or burnt and to maintain soil fertility minimal tillage or direct drilling techniques should be adopted.

Stockdill (1959) observed that in New Zealand soils in the absence of earthworms all dung and dead vegetation had accumulated on the surface to a depth of about 12 mm while the soil beneath lacked organic matter and was of poor structure. These results were supported by Edwards (1981) who claimed that soils poor in earthworms often had a mat of undecomposed organic matter at the soil surface.

(e) Effects of earthworms on plant growth:

There is a considerable body of evidence in the scientific literature to show that earthworm activity in soil favours plant growth. The earthworms have apparently provided channels ideal for root growth, and increased soil drainage and aeration. It has also been reported to be difficult to separate the relative contributions of these different factors in improving soil fertility (Edwards, 1981; Edwards and Lofty, 1977; Stockdill, 1959; Lal, 1978).

When root growth was not restricted by physical properties of the soil, such as temperature and aeration, the main physical factor controlling root growth seemed to be soil strength (Barley and Graecen, 1967), which varied with bulk density and water content of the soil (Camp and Lund, 1968). In this respect, Ehlers et al (1983) under a no-till system on non-swelling loess soil, claimed that in tilled and untilled soil, soil strength appeared to be the main physical factor controlling root growth. They found that in tilled soil, mechanically produced planes of weakness seemed to influence penetration resistance and probably root growth, depending in part, on their number and extention per unit volume of soil. Also in a rigid soil matrix of untilled soil, roots followed pathways of low, or practically no resistance, according to Ehlers et al (loc cit). They concluded that these were either channels created by earthworms or smaller pores created by the roots of preceding crops, and the percentage of roots growing in these channels was higher in untilled soil, particularly in deeper layers of the soil. Most of the roots were thriving within these channels and the number of roots in the bulk soil was minimal.

Edwards and Lofty (1980) supported these findings and claimed that on untilled plots the root growth and yields of barley were significantly higher than on tilled plots with less numbers of earthworms. They commented that most of the effects seemed to be due to the provision of channels for root growth but these might have been enhanced by the placement of essential nutrients in earthworm burrows.

There is evidence from field experiments in New Zealand that the addition of European species of earthworms to sown pastures could increase crop yields by 28-100 % (Stockdill, loc cit; Waters, 1955). "It has been estimated that in New Zealand earthworm introduction could increase the carrying capacity of at least 3.25 million hectares of pastures between 1 and 2.5 stock units per hectare over a period of the next two decades. This represents a potential increase in annual export earnings of between $120 million and $300 million per annum for an initial single investment of about $10 per hectare ($32.5 millon)" (Springett, 1983a).

Even although there is useful knowledge about the role of earthworm activity in increasing crop growth, there is little or no information available indicating the effects of earthworms on root development and crop yields in association with drilling openers in direct drilling systems, particularly under wet soil conditions.

2.3. SOIL OXYGEN AND PLANT GROWTH

Soil aeration is one of the more important determinants of soil productivity. Lemon and Erickson (1952) claimed that Russell believed that evaluation of conditions at the interface between the root surface and the soil system presented the greatest possibility of ascertaining the influence of soil aeration on plant growth. As the active root surfaces were covered with water films, this interface was the cell-wall-liquid-face of the root and the water film. Movement of oxygen from the atmosphere to the actively respiring cells of the plant root, therefore, involved not only diffusion through the gaseous phase of the soil but also movement through the gas-liquid-phase boundary. In the water-film-cell-wall portion of the oxygen chain, movement was probably by diffusion only. Under normal conditions the direction of oxygen diffusion was down a concentration gradient from the soil atmosphere into and through the water films of the soil to cell walls of the roots. This concentration gradient may at times, if not always have been very marked.

(a) Diffusion in gaseous phase:

Diffusion of gases through the soil depends not only upon the concentration gradient of the gas but upon the ability of the soil to transmit the gas.

Apparently changes in the soil bulk density resulted in changes in oxygen diffusion rate in the soil. For example, Bertrand and Kohnke (1957) observed that oxygen diffusion rate was slower in dense than in loose soils. They concluded that restricted root growth in a dense soil was partly the result of the subsoil acting as a mechanical impedance, and partly due to lack of oxygen. These findings were supported by Raney (1949) who claimed that diffusion rates for regular ploughing and subsurface tillage were similar. Disced and rotary hoed plots gave higher values for soil bulk density and lower diffusion rates, according to Raney (loc cit). He observed general agreement between diffusion rates and yields of vegetables. Taylor (1949) showed that oxygen diffusion rate was reduced by increasing bulk density, but the changes were not independent of the material used. He felt that entrapped air and shape of the particles had an influence. However, he proposed that the diffusion impedance, rather than relative diffusion rate, be used to characterise soil aeration.

(b) Diffusion in liquid phase:

" The final segment of the diffusion path to a root must take place through the hydration film or shell surrounding the root". (Hillel, 1980).

Lemon and Erickson (1952) had already made a similar statement, as active root surfaces were covered with a water film, and since oxygen was only slightly soluble in water, the oxygen diffusion rate in the soil was considered an important factor (and not necessarily only the absolute percentage of oxygen). According to these authors the thickness of water film on the root was quite important to oxygen movement.

Taylor (1949) made a careful analysis of different soil factors that affected the so-called "effective diffusion distance". In studying the influence of moisture and the effect of time on partial pressure of oxygen resulting from diffusion through a core of Ontario loam of uniform density, he observed great differences due to varying amounts of moisture. When investigating the relation of diffusion in soils at different moisture tensions, he found that very little diffusion took place at tensions lower than 20 cm of water. At tensions higher than 30 cm, there was little effect of moisture on diffusion, a conclusion which was in agreement with that of Kristensen and Lemon (1964).

(c) Direct Drilling and soil aeration:

" Tillage can have a profound effect on aeration of soil, with the magnitude of change depending upon the initial soil properties. For example, tillage of a dense soil with poor aeration characteristics with the proper tool at the right moisture conditions can correct, temporarily, the aeration problem. A coarse textured or well aggregated soil without an aeration problem cannot be improved by tillage and is a prime candidate for no-tillage agriculture" (Erickson,1982). Burnet and Houser (1968) felt that deep tillage was not a panacea for all crop production problems associated with physical or chemical soil properties.

Where certain soil factors that limited plant growth could be identified deep tillage might have been beneficial.

Several authors claimed that more restricted aeration might be expected in untilled soils due to higher bulk densities (Triplett et al, 1969; Soane et al, 1975; Cannel and Finney,1973; Baeumer,1970). On the other hand, aeration may have been promoted in untilled soils as the cracking of the soils in dry weather had not been destroyed by crop cultivation (Ehlers,1975). Dowdell et al (1979) reported that anaerobic soil conditions were expected when soil was compacted in direct drilling because of the restricted entry of oxygen especially in wet soils. However, no large decrease in concentration of oxygen in soil appeared to have been caused by direct drilling. Direct drilling resulted in higher oxygen concentration than ploughing during wetter winters (averaging 10.2 and 7.2%, respectively). They felt that a higher oxygen concentration found following direct drilling was possible due to a system of large pores and earthworm channels which developed in direct drilled plots, but which were destroyed by annual ploughing. These findings were supported by Erickson (loc cit) in wet soils.

It is evident from the literature that while some measurements have been made of these factors in the general soil matrix, few attempts have been made to highlight the results of specified direct drilling opener designs through untilled soils. Even less interest has been shown in separating the physical soil properties in the groove from those of the undisturbed matrix between the grooves, or of the interface between the two. No specific information relating to oxygen concentration around the groove profile is available when crop residue is pushed into the groove and decomposed during a wet season.

(d) Plant responses to soil oxygen diffusion rates:

After oxygen diffusion rates (ODR) have been measured and calculated, they must be empirically related to plant responses.

(i) Root growth and ODR

Root elongation is one plant function that apparently, has critical ODR values. Stolzy et al (1961) showed that root growth of snapdragon reduced or stopped when ODR in the soil was 18 to $23x10^{-8}$ $gm/cm^2/min$. Oxygen diffusion rates above $23x10^{-8}$ $gm/cm^2/min$ permitted relatively good growth. Letey et al (1961a) studied the effect of temperature and ODR on sunflower(*Helianthus annuus*) and cotton, and concluded that ODR values of approximately $20x10^{-8}$ $gm/cm^2/min$ prevented root growth, independent of temperature. In another experiment with sunflower growth at different soil and air temperatures, roots failed to grow when the ODR was less than $20x10^{-8}$ $gm/cm^2/min$ (Letey et al, 1962a).

A study with blue grass (*Poa Pratensis*) showed that an ODR of $20x10^{-8}$ $gm/cm^2/min$ was required for root growth (Letey et al,1964). The optimum , however, was an ODR of $40x10^{-8}$ $gm/cm^2/min$. Barley (*Hordeum Vulgare*) had a higher tolerance for low oxygen and could grow roots at an ODR value as low as $15x10^{-8}$ $gm/cm^2/min$ (Letey et al, 1962b). Other authors (Bertrad and Kohnke, 1957) used bulk density and the distance to a water table as variables, and found that ODR values below 20 to $30x10^{-8}$ $gm/cm^2/min$ were detrimental to root growth of corn. Van Diest (1962) claimed that the least number of roots were counted in the compacted plots with ODR values of $13x10^{-8}$ $gm/cm^2/min$, while the aerated plots had the most roots, and ODR values of 36 to $41x10^{-8}$ $gm/cm^2/min$.

Data from various investigators suggest that an ODR value about $20x10^{-8}$ $gm/cm^2/min$ inhibited root growth of most crops. Values between 20 and $30x10^{-8}$ $gm/cm^2/min$ retarded root growth. However, this has depended upon such physical factors as soil type, soil moisture content, soil bulk density, drained or undrained and the distance of the water table below the soil surface. Little information is available relating ODR values and the geometry of various grooves in direct drilling.

(ii) Shoot growth and ODR:

The effect of soil oxygen on shoot growth has been important in controlled studies with different degrees of soil aeration. Because of differences in ODR values in various parts of the roots, however, it has been difficult to assess a single value as critical. Studies by Letey et al (1961a, 1962a, 1962b, 1964) showed a pronounced effect of reduced soil aeration on shoot growth. One study (Letey,1962a) on sunflower showed that as a very general guide, diffusion rates greater than $40x10^{-8}$ $gm/cm^2/min$ could be considered near optimum for shoot growth. However, according to these authors, the optimum diffusion rate for barley was less than 40×10^{-8} gm/cm^2/min.

Lemon and Erickson (1952), using different distances to water table to control ODR, found values of 30 to 40×10^{-8} gm/cm^2/min at 200 mm soil depth critical for tomato (Lycopersicon esculentum) plants (although these authors did not specify that the observations were on shoot growth alone). Bertrand and Kohnke (1957) studied corn using soil bulk density and distance to free water as a means of varying oxygen. They found that shoot growth increased as ODR increased to about 19×10^{-8} gm/cm^2/min when -0.65 V potential was applied. However, Van Diest (1962) found no difference in shoot growth of corn due to differences in soil ODR. His values varied from a low ODR of 10×10^{-8} gm/cm^2/min, on compacted soil, to a high of 50×10^{-8} gm/cm^2/min on aerated soil. This author did not explain the reason for the absence of differences in shoot growth at different levels of ODR.

"Information on ODR in relation to plant growth indicates that soil oxygen has a wide range of influence on the species and the stage of growth. For plants in the vegetative stage, ODR values of 40×10^{-8} gm/cm^2/min or less are critical; at flower and fruit producing stages the optimum ODR is somewhat higher. Plant species vary in their response to low oxygen". (Stolzy and Letey, 1964).

(e) Measurement of soil aeration status:

According to Taylor and Ashcroft (1972), there were three properties of soil air that were of interest in crop production studies. These were: the aeration porosity, the chemical composition of gases, and the rate of exchange of gases. The latter involved the mass flow of gaseous phase and also the diffusion of dissolved gases through soil solution to an oxygen absorbing root.

Several methods have been used to measure the soil aeration status. An early approach to the problem of measuring soil aeration was to determine the fractional air space, or "air filled porosity", at some standardised value of matrix potential.

Russell (1949) and Page (1947) considered air space as a function of total porosity and they used an apparatus called an "air picnometer" for laboratory measurements of air filled porosity.

Taylor and Ashcraft (loc cit) stated that "The composition of the gases in the soil is constantly changing. A determination of gaseous exchange is, therefore, valid only for the time the gas sample is taken, and may not be representative of the average composition or the composition for some other time. There are several objections to aspirating samples from the soil for analysis:

1. The source of sample is never known. There might be small or large pores in the vicinity of the sampling tube or the sample might stream out of the large pores or even come directly from the atmosphere through the large pores.

2. It is unlikely that such samples are in equilibrium with the gases that are dissolved in the soil solution.

3. It is not possible to determine the amount of gases per unit volume of soil but only the relative concentration; it is desirable to know both".

However, according to Yamaguchi et al (1962), a gas chromatographic technique, using a syringe to extract small samples (0.5 ml in volume) helped to make the measurements more reliable. The usefulness of this technique has been supported by several authors (Lai et al, 1976; Dowdell et al, 1979). Dowdell et al (loc cit) used this technique to determine oxygen concentration while comparing the effects of different tillage techniques on soil properties including direct drilling. An alternative method permitting repeated monitoring of oxygen concentration in soil without extraction of samples was based on the use of membrane-covered electrodes, such as described by Williams and Willardson (1964).

Hillel (1980) stated that a quite different approach to characterising soil aeration was to measure the air "permeability", such as the coefficient governing convective transmission of air through the soil in response to a total pressure gradient. This measurement could provide useful information on effective sizes and the continuity of air filled pores. The techniques which had been used included constant pressure and falling pressure devices. Grover (1956) applied these methods in the field and found them useful for assessing the "openness" of the surface layer to the entry of air, as affected by such cultural practices as tractor traffic and tillage

Other techniques have been proposed for measuring diffusion processes in the soil, both in the gas phase and liquid phase. Kristensen and Lemon (1964) emphasized the importance of soil parameters such as "apparent liquid path length" for diffusion, the "effective diffusion coefficient" in soil and the oxygen concentration in soil air (liquid-gas interface). These authors integrated oxygen supply characteristics of soil, as measured with platinum micro-electrodes, with oxygen demand characteristics of plant roots. They commented that platinum micro-electodes could be used for measurement of oxygen diffusion only when the soil was sufficient wet, so that the only factor limiting the current flow was oxygen diffusion. This may not have been a serious draw-back for the method, as it was in such soils that the aeration problem occurred.

McIntyre (1970) made a severe critique of the method for measuring ODR with platinum micro-electrodes. But the previous and subsequent reviews indicated that the technique of platinum micro-electrodes, to measure oxygen diffusion rate in the soil, had been considered simple, economical and probably functioned properly for measuring soil aeration status in situ (Lemon and Erickson, 1952; Birkle et al, 1964; Letey and Stolzy, 1964; Erickson, 1982). Erickson (loc cit) recommended the platinum micro-electrode method for measuring oxygen diffusion rate to study the effects of tillage on soil aeration in terms that were related to plant growth.

2.4. DESIGN PARAMETERS OF DIRECT DRILLING OPENERS

Suitable design specifications for direct drilling openers are essential for obtaining satisfactory performance in a range of field conditions. It is clear that the soil micro-environment in seed grooves created by direct drilling openers in dry soils has affected seed germination and seedling emergence. In this respect, Choudhary and Baker (1981) proposed specific functionsfor direct driling openers and covering devices based on their detailed research of the seed soil micro-environment created by a range of opener designs in these dry conditions.

2.4.1 Opener functions:

A planter or seed drill performs two major functions:

1.To meter and distribute the seed (and fertilizer).
2.To place the seed (and fertilizer) into the soil.

Seed metering and distribution are independent of soil conditions, but placement of seed in the soil is affected by the conditions of the soil in which the planter or seed drill operates.

2.4.2 Design and modifications of drills for direct drilling

Several advances have been made to the openers of drills for tilled seedbeds, in order to improve penetration of untilled soil and undisturbed residue; to reduce blockage from residue; and to more accurately control seed and fertilizer placement. These modifications are reviewed below:

(a) Openers with rolling components:

A common modification of conventional openers for planting in no-tillage conditions has been to mount a rolling disc coulter in front of the furrow opener. The functions of the rolling disc coulters have been to cut plant residue and to till a narrow strip of soil, thereby enabling the furrow opener to penetrate to the desired depth and the furrow-closing mechanism to cover the seed (Allen et al, 1975; Carreker et al, 1972; Gard and McKibben, 1973; Triplett et al, 1963).

Allen et al (loc cit) used a fluted disc coulter in front of a double disc opener on a maize planter. The fluted coulter cut residue and loosened a zone of soil about 60 mm wide by 75 mm deep. Gard and McKibben (loc cit) used a no-till maize planter with openers which consisted of a ripple disc coulter, a narrow runner opener behind and in line with the coulter, an angled disc coulter to close the seed furrow, and a press wheel for depth control. Triplett et al (loc cit) used a serrated rolling disc coulter ahead of a 360 mm wide flat sweep operating 100 mm deep, followed by three rotary hoe wheels which "conditioned" the soil in front of a furrow opener.

Most of the no-tillage drilling in the United Kingdom had been done with triple disc planters (Logan and Gowman, 1977), until recently (P.D. Aitchison, pers.comm, 1984). In the USA, Morrison and Abrams (1978) developed an experimental triple disc opener assembly that used a rolling disc coulter ahead of a double disc opener. The trailing portion of the smooth rolling coulter was located between the discs of the double-disc opener. Angled wheels were used to close the furrow.

A drill developed at the Scottish Institute of Agricultural Engineering used a single disc coulter followed by a self-sharpening A-blade opener with angled lateral wings (Butterworth, 1980). The angled wings lifted soil to either side of the rolling coulter slit and formed planting cavities beneath the soil. Baker et al (1979a) developed a winged opener, which they first called a "chisel coulter", for no-tillage drilling. The rolling disc coulter cut plant residue, and the side blades widened the furrow and lifted two strips of soil under which seed and fertilizer were placed.

Decker et al (1964), Jones et al (1979), and Squires et al (1979), in their evaluations of furrow openers for planting in sod described the openers as using combinations of rolling disc coulters and hoe openers to clear a strip of soil into which the seeds were planted.

(b) Openers with powered components:

Logan and Gowan (1977) evaluated two machines for planting with no previous tillage. The first was a modified rotary cultivator that made 20 mm slots at 125 mm spacings. The second was a rotary cultivator that revolved against the direction of travel and could be adjusted against the direction of travel by angling the rotor to vary the slot width.

Smith et al (1967) developed a powered disc furrow opener, and Smith et al (1973) used the device for furrow openers on a grassland renovator, which was later commercialised by John Deer Ltd. (C.J.Baker, pers.comm, 1982). Erbach (1978) developed furrow openers with powered disc coulters, for planting without previous tillage. One used a hoe furrow opener, and as plant residue slid over the top of the opener, it was sheared by the powered serrated coulter. Others used powered serrated coulters driven in a reverse direction of travel in order to open a slot ahead of a runner or double disc furrow openers. The coulters were run in a reverse direction to prevent plant residues from being pulled into the seed zone.

Buchele (1979) developed a rotary tiller slot planter with rotary blades mounted on either side of a split-tube chisel furrow opener. The rotary blades cleared plant residue from the chisel and tilled the soil in the seed zone.

It is interesting to note that most of the openers referred to above performed a degree of tillage as a primary function, but there have been no specific data offered to support the need for tillage of this nature.

(c) Openers for fertilizer placement:

One of the earliest reports of a special tool for separating seed and fertilizer in direct drilling grooves was by Hyde et al (1979). They opted for vertical separation. Soon after Baker et al (1979b) reported a device for horizontal separation. They applied fertilizer to one side and seed to the other side with their winged ("chisel") opener assembly. Some authors described planters with split-tube hoe openers in which fertilizer was dropped down the front tube and soil was placed over the fertilizer to separate it from the seed. The other was dropped down to the rear tube (Buchele,1979; Decker et al,1964; Jones et al, 1969; Triplett et al, 1963).

2.4.3 Performance of openers and modifications for no-tillage

Formation of the seed groove :

A rolling disc coulter often improved opener operation in no-tillage, according to Allen et al (1975); Logan and Gowman (1977); Morrison (1978); Richey and Griffith (1977). Allen et al (loc cit) reported that a fluted coulter disc mounted in front of a unit planter provided more uniform seed placement at a desired depth in large amounts of residue than did a grain drill with single-disc furrow openers. Erbach (1980) quoted Krall who had apparently concluded that a straight disc coulter ahead of double disc openers worked well when planting into standing stubble. Logan and Gowman (loc cit) found that a fluted disc coulter mounted either ahead of or behind double disc openers improved in-furrow soil conditions in a wet clay soil. Erbach (loc cit) reported that Gallaher found in 1980 that coulters with a serrated edge cut better and needed less weight for penetration but did less tillage than rippled and fluted coulters.

When soil was wet and loose, a disc coulter was reported to press residue into the seed zone. If the coulter was set deep enough to cut the residue, it could turn up wet soil and plant roots that clogged planter furrow-closing devices. When the soil was dry , it was often difficult for the coulter to penetrate and to loosen enough soil for uniform seed coverage. Baker et al (1979a) found that discs could not be relied upon to cut all residue, but a portion could be expected to be deflected or pushed into soft soil. The winged ("chisel") opener developed by Baker et al (1979a) was followed by press wheels, and the combination was reported to create a good seed and seedling environment in dry soil conditions.

Draught penetration force requirements of direct drilling openers are a function of opener design and operating conditions of the soil. For example, Koronka (1973) reported that opener draught and the force required for penetration were generally lower for triple disc openers than for disc-hoe openers. He concluded that a triple disc opener penetrated residue better and wear was more even than a disc-hoe opener, but the triple disc did not work well in stony soils. Baker et al (1979) reported that the draught for their winged ("chisel") opener was greater than that for triple disc or hoe openers but the penetration force was similar. Koronka (loc cit) and Logan and Gowman (loc cit) found that tip wear of a hoe opener was rapid and that, when the tip was worn, penetration was poor and draught was high.

In hard soil, apparently neither runner nor disc furrow openers penetrated well. In wet conditions, both disc and runner furrow openers have been reported to smear the furrow walls (Dixon, 1972). Hoe openers penetrated soil under most conditions but became blocked with residue (Baker, 1981). In this respect, Lindwall and Anderson (1977) found that double disc and triple disc drills generally failed to penetrate untilled surfaces adequately when the soil bulk density in the upper 50 mm exceeded 1.2 gm/cm^3 or when the quantity of surface residue exceeded 3,700 kg/ha. However, according to these authors, hoe openers penetrated the soil but failed to clear heavy residue when stubble and straw lengths were greater than 250 mm. They also claimed that in wheel traffic areas the disc openers did not penetrate and gave planting problems.

Interference between adjacent drill furrow openers and between components of the same drill unit could cause blockage with residue or poor performance. Baker et al (1979a) found that plant residue could not be cleared with non rolling components spaced 150 mm apart unless the components were in partial or intimate contact with accompanying discs or were so angled or shaped that residue could be deflected under, over, or to one side. Multiple opener assemblies did not always clear as much residue as a single opener having unlimited side clearance. Baker et al (loc cit) found that the problems of "soil waves" from one opener interfering with the operation of adjacent openers could be eliminated by staggering ranks of furrow openers usually but only if the stagger was relatively large. Erbach (1978) noted that depth control wheels should be located near the point of seed discharge but they must be in contact with stable soils. He claimed that if these wheels were running on soil that was in motion (because of the action of the furrow opener) the wheels might not roll, and might push residue and soil and thus become blocked.

2.4.4 Physical, biological and chemical influence of groove openers in direct drilling

Little work has been reported in the literature on the physical, biological and chemical influence of openers in direct drilling. The opener designs most critically tested have been a commercial triple disc opener with plain front disc (which usually formed a neat "V"-shaped groove); a commercially availabe hoe opener (which usually formed a torn or shattered "U"-shaped groove); and an experimental winged ("chisel") opener preceded by a plain front disc (which formed an inverted "T"-shaped groove, torn or shattered beneath the surface). The latter device was developed at Massey Universty, New Zealand, and was later succeeded by a more advanced design centered on a scalloped disc with angled side blades rubbing on either side of the disc, but which continued to form an inverted "T"-shaped groove (Baker, 1976a; Baker, 1979c). The seed groove micro-environments studied can be categorised into physical, biological and chemical influences of the furrow opener design.

(a) Seed groove micro-environment -physical:

Moisture status:

The effects of various opener designs on the moisture status of direct drilled seed grooves has been the subject of recent investigations. Choudhary (1979) was able to show that, although liquid soil moisture was required for seed germination, moisture in the vapour phase was responsible for sub-surface seedling survival. The type of seed groove cover was important in affecting the relation of groove moisture vapour. A winged ("chisel") opener (Baker, 1976a) which was reported to utilize a vegetative mulch of relatively undisturbed sod or other residue to cover the seed groove, was shown to more effectively retain groove vapour moisture and thereby promote seedling emergence than either hoe or triple disc openers in dry soils (Choudhary, loc cit; Baker, 1976a,b; Choudhary and Baker, 1980). Choudhary(loc cit) also found that when a triple disc opener was employed the in-groove relative humidity decreased at a rate of 4.23% per day for the first six days after sowing. This rate was significantly higher than that of the winged opener groove (2.34%) and hoe opener groove (2.75%). Choudhary (loc cit) also felt that the winged opener left the seed groove well covered by a vegetative mulch and separated the seed from the atmosphere. This accounted for the slower drying rates, while the triple disc opener left the seed groove open to the atmosphere and thus lost moisture vapour quickly. However, under moist soil conditions these opener designs did not differ in their effect on in-groove relative humidity, according to Follas(1982).

Mechanical impedance:

Acording to Russell (1977), "Soil mechanical impedance is a phenomenon which effects seed and seedling emergence in two distinct ways; impedance to the root system and impedance to the seedling emergence. The root has a plastic property. The path of growth would be along the line of least resistance. When growing roots encounter pores in a solid medium which are smaller than their diameter, continuing extension is possible only if they are able to exert sufficient pressure to expand pores or to decrease in diameter thus passing through existing pores". Many authors have indicated that soil crust strength limited seedling emergence and growth in tilled soils (Hanks and Thorpe, 1956a,b; Taylor et al, 1966a; Ehlers et al, 1983), but little similar work has been undertaken in no-till soils.

It appears that soil bulk density and mechnical impedance are dominant factors in the development of roots and shoots. Compaction of the base of the seed groove and smearing of the side walls have been reported for a triple disc opener (Baker, 1976; Dixon, 1972; Mai, 1978; Mai and Baker, 1982). Dixon (loc cit) identified the zone of influence (regarding compaction, smearing and soil shattering) of the grooves created by winged, triple disc and hoe openers at different levels of "available" soil moisture contents at the time of drilling (Appendix 1a). Mai (loc cit) clearly described the zone of influence created by the winged and triple disc openers. This zone of influence was approximately

45-55 mm either side from the centre of the groove and about 50 mm down from the base of the groove (Appendix 1b). J. Mitchell (pers.comm.1983) supported the results of the above two authors and was able to define more clearly the zone of influence of the grooves of winged, triple disc and hoe openers. Her "iso-soil-strength" lines (Appendix 1Ci, 1Cii, 1Ciii) indicated the shape of the zone of influence of the three opener types on either side and base of their respective grooves.

While seed groove compaction might have occurred with some openers, it was unlikely to impede the penetration of roots of direct drilled seeds until soil bulk density became high (Baker and Mai, 1982). These authors found that when initial soil bulk densities were favourable (1.0-1.04 g/cm^3), resulting compaction to 1.15-1.18 g/cm^3 with a triple disc opener groove had little or no noticeable effect on seedling root development of either lupin (Lupinus sp) or wheat (Tricitcum aestivum). However, when the intial bulk density was 1.32 g/cm^3, a resulting compaction arising from the triple disc opener (1.44 gm/cm^3) had a marked effect on lupin root development and in some instances caused deterioration and deflection. This appeared regardless of whether or not the grooves had been allowed to dry after drilling or had remained moist thereafter. In contrast to this, a winged opener was reported to have had a tendency to decompact the seed groove and did not impede emergence or root growth in any of the soils tested.

As described earlier seedling emergence can be influenced by soil strength. In his respect, Choudhary (1979) investigated the effects of, and measured impedance to penetration of soil above the seed using a rigid needle pushed up from beneath. He found a trend for higher energy expenditure for penetration through the soil surface when a hoe opener was used (119.1×10^{-3} Nm) compared with winged (99.1×10^{-3} Nm) and triple disc (97×10^{-3} Nm) openers. Further, the application of 70 kPa press-wheel pressure by the opener directly over the covered seed groove increased the energy expenditure by approximately 28% compared with when 0 or 35 kPa press-wheel pressures were applied. However, visual examination of emerged wheat seedlings in these experiments failed to reveal any effect which might have been attributed to soil resistance. Choudhary (loc cit) characterised the hoe opener groove by the quantity of loose soil (due to shattering) compared with the more cleanly cut triple disc opener groove, and somewhat hollow nature of the winged opener groove. It was perhaps not surprising, therefore, that the mechanical seedling he used encountered slightly higher penetration forces in the hoe opener grooves compared with the winged and triple disc opener grooves. In any case Choudhary and Baker (1977) claimed that soil penetration resistance noted under varying humidity conditions with the different openers were in the range of 7000 mbars (for most cereals) which had earlier been described as being favourable by Taylor et al (1966a). Thus it was possible that soil impedance, per se in these experiments was of a level likely to have had little effect on seedling emergence of cereals.

Soil temperture:

Many soil properties influence soil temperature, but soil bulk density, porosity, moisture content and the presence or absence of surface mulch are apparently those most likely to be affected by cultivation. Specific information available in relation to in-groove temperature, as affected by opener design, is not extensive. In this respect trials conducted under dry soil conditions at Massey University, New Zealand, have indicated little or no effect of the geometry of the groove on in-groove soil temperatures. For example, neither Baker (1976) nor Choudhary (1979) were able to detect any significant differences amongst direct drilling opener types in the mean day and night temperatures even although large differences in seedling emergence were noted. However, Baker (loc cit) found that in-groove minimum temperature of the winged opener groove was slightly (although) significantly higher than both the hoe or triple disc opener grooves. Under continuously drying conditions Choudhary and Baker (1977) reported a steady increase in in-groove temperature of 0.5^{o} C and 1^{o} C (day and night respectively) with all the above openers. They felt that these temperature changes were merely reflections of changes in liquid soil moisture contents and that they would have had only minor effects on seed germination.

It appeared, therefore, that opener design had little effect on seed-groove temperature. This was also confirmed by Follas (1982) under moist soil conditions (slightly higher than field capacity). He observed that triple disc opener grooves had slightly higher temperatures than winged and hoe opener grooves, but was unable to explain the reason for this.

Soil aeration:

Seed germination is a process which involves the respiration of living cells and consequently requires an adequate supply of oxygen (Mayer and Poljkoff-Mayber, 1963). Some work has been reported on the soil aeration status in the general matrix of the soil as affected by direct drilling and ploughing (Dowdell et al, 1979; Triplett et al, 1968). However, in direct drilling there appears to be little or no information regarding the effect of opener designs on soil aeration. Similarly, while it is possible that soil aeration problems would be more common in water-logged soils, there appears to be a lack of information regarding the possible extent of soil aeration problems in relation to the performance of direct drilled seeds. It has, therefore, not been possible to specify design criteria for direct drilling machines in terms of seed groove aeration parameters.

(b) Seed groove micro-environment - biological:

Earthworms:

Little information is available relating the influence of opener designs to in-groove earthworm populations and activity, particularly where their presence might have affected the seed-soil micro-environment. In this respect, Mai (1978) attempted to obtain a measure of the population of earthworms in direct drilled grooves and to observe if there were any interactions between earthworm populations and drilling and compaction treatments in his comparison of two openers. He observed that populations of earthworms were not significantly affected by soil density or opener treatments with wheat or lupin on day 21 after drilling. However, on day 35, there was a significantly higher earthworm population in the plots using a winged opener compared with those using a triple disc opener.

It was also noted that in these treatments the total numbers of earthworms had increased between days 14 and 35, although this trend was not analysed statistically. However, these findings confirmed the results of Lal (1976) who claimed that earthworm activity under no-tillage increased with increased time after drilling. Mai (loc cit) had been unable to explain the reason for the difference in earthworm activity in the different grooves.

Fungi:

Fungi that grow on or in seeds can be divided into two groups -field fungi and storage fungi. Many field fungi are soil borne due to crop residues. They are high humidity or high moisture growing organisms (M.J. Hill, pers comm, 1982). It has been reported that straw provided substrates for both the growth of micro-orgnisms and the formation of microbial products (Barber and Standell, 1976). The inhibition of seed germination and seedling establishment could have been the result of the action of microbes, directly or indirectly, or by their metabolites.

Letcombe Laboratories in the United Kingdom published a series of reports indicating the effects of fungi on seed germination and seedling growth. They claimed that compared with conventional tillage, direct drilling encouraged the development of a more diverse microflora which was concentrated in the upper layers of the soil. They felt that if, during the process of drilling, additional organic matter was incorporated into the soil (as may have occurred if straw remained from the previous crops) the microbial activity would be further stimulated. It was therefore not surprising (in their views) that in such circumstances conditions adversely affecting the establishment of direct drilled crops might rapidly develop. These findings were confirmed by Lynch (1977).

Lynch et al (1977) later also claimed that early growth of roots and shoots was poorest in the presence of straw when the seeds were lodged tightly in "V"-shaped slits made by triple disc openers. They attributed this in part, to the development of fungus colonies on the seeds. This was confirmed by Penn and Lynch (1980) in glasshouse experiments on barley seeds and seedlings.

Little information is available regarding the interrelationship between opener designs and seed groove fungi development. However, the work by Choudhary and Baker (1981) showed that an artificially created high moisture zone in a triple disc groove (which was created by a polythene cover over the groove) allowed full seed germination but was accompanied by strong evidence of fungal growth within the groove and on the seedlings. As a result 37% of the seedlings died.

It appears that no comparative studies using other opener designs have been made. It is therefore, not surprising that no authors have offered clear conclusions relating to the effects of machine design on fungi development in the presence or absence of crop residues under wet soil conditions.

(c) Seed groove micro-environments - chemical:

Toxicity:

It has been reported that seed germination and seedling growth in a direct drilled groove can be impeded by phytotoxic effects of decomposing crop residues, anaerobic conditions of the soil and the position of fertilizer placement in the groove. Phytotoxic effects of crop residues have already been discussed under the heading of "chemical influence of crop residues". (Section 2.1.3).

Little information regarding in-groove toxicity from fertilizer in relation to opener designs is available. Afzal (1981), in applying ammonium sulphate (21-0-0) at an equivalent rate of 360 kg/ha (75 kg/ha of N), together with rape (Brassica napus) seed in grooves created by a winged ("chisel") opener, found toxicity, but only when fertilizer was vertically separated from the seed, mixed with the seed, or horizontally separated from the seed by 10 mm or less. However, he also found evidence of reduced toxicity where the horizontal separation distance was 20 mm. These findings have been supported in a report from Scottish Institute of Agricultural Engineering which indicated that fertilizer should be placed to one side of the seed and slightly above it so that it could be distributed by water percolating through the soil, and should not cause damage to the seed (Buston, 1978). The Scottish Institute of Agricultural Engineering designed an "A"-blade drill to separate seed and fertilizer from each other in this manner.

3. EXPERIMENTS

3.1 FIELD COMPARISONS OF DIRECT DRILLING OPENER PERFORMANCE. (Experiment 1)

3.1.1 Introduction:

Little information has been available regarding the comparative performances of direct drilling openers in the presence or absence of crop residue under wet soil conditions. In order that broad responses of seeds and seedlings to the grooves of different direct drilling openers, in the presence or absence of surface residue and varying soil moisture status, might be obtained, a comprehensive field experiment was conducted in a soil (Tokomaru silt-loam) of poor natural internal drainage characteristics (Pollok, 1975).

3.1.2 Materials and methods:

(a) Preparation of surface residue conditions:

Many reports in the literature had indicated possible adverse effects from the herbicides glyphosate and paraquat on seed germination and seedling growth (Warboys, 1974; Klingman and Murray, 1976; Choudhary, 1979; Faulkner, 1980). In this respect, Davies and Davies (1981) claimed that adverse effects of glyphosate (at 1.44 kg/ha) on seedling growth were minimal when seeds were sown 14 days after spraying and were reduced to almost nil after 21 days. Little information was available on possible adverse effects of dicamba on seedling growth, as this chemical had almost always been used in combination with the other two herbicides named above. Accordingly, the pasture was sprayed with glyphosate and dicamba 28 days before the seed drilling operation.

Three residue conditions were imposed. These were; "bare soil", "short residue" and "long residue". All residue conditions were on irrigated and non-irrigated soil.

In a field of Tokomaru silt-loam soil, under a permanent rye grass (Lolium sp) and white clover (Trifolium repens) pasture, an area (71x52 m^2) was sprayed with 5.6 l/ha glyphosate plus 1.5 l/ha dicamba using a knap-sack sprayer. After 7 days the grass on the sprayed area was mown to ground level with a garden type rotary mower. The mown area was sprayed again to kill close-growing under-canopy vegetation. At the same time the balance of the area was sprayed to prepare "short" and "long" crop residue. After a further 14 days the area designated for "short residue" was cut about 40 mm above the soil surface (equivalent to approximately 1000 kg DM/ha remaining), while the "long residue" was left about 200 mm long (equivalent to approximately 3000 kg DM/ha remaining).

(b) Opener types: Selection:

There are a variety of direct drilling openers available, both commercially and experimentally. These include opener assemblies with chisels, discs, sweeps and powered rotary strip tillers. The variety of direct drilling machines available demonstrates that no one machine is yet recognised as providing satisfactory results under all field conditions.

However, most openers have been developed with the following common points in mind.

One pass operation.
Trash handling ability.
Satisfactory wear rates.
Ability to penetrate uncultivated soils.
Depth control.
Provision of seed cover.
Sufficient structural strength.
Adequate work rate.

Three selected openers appeared to provide contrasting groove shapes and also exhibit different reactions to surface residue. The salient features of each opener are described below.

(i) Winged Opener

The winged opener is shown in Figure 1. It was developed and assembled at Massey University, New Zealand. In the form it was tested, it was almost ready for commercial release. This version of the opener featured a 450 mm diameter scalloped disc with side blades located on each side of the disc. The base of these side blades formed wings which created a degree of soil shattering, because of their 5^{o} angle to the horizontal. Seed and fertilizer were directed separately down either of the side blades. A pair of angled depth control/press wheels trailed behind the side blades. These wheels closed the groove slit in such a way that the soil and surface residue was folded back from whence they came. In this way an inverted "T" shaped groove of approximately 40 mm width at the base, was created, and surface residue was not pushed down into the groove.

(ii) Triple Disc Opener

The triple disc opener was an early commercially available assembly (P and D Duncan Ltd; Figure 2) and consisted of a flat vertical pre-disc of 325-mm diameter followed by two flat discs angled towards each other at approximately 15^{o}. A narrow "V" shaped slit was formed approximately 40 mm in width at the surface (Koronka, 1973). Little damage or disturbance to the soil was created by this opener. Under surface residue conditions, trash was sometimes pushed into the groove close to the seed (Christian and Ellis, 1977). Surface residue was not pushed bodily aside.

(iii) Hoe Opener

The hoe opener used was also a commercially available unit (P and D Duncan Ltd, Figure 3). It consisted of a flat vertical pre-disc (250-mm dia) followed by a tapered hoe tool. The horizontal cross section of the tool at ground level was 35 mm from the point to tail and 40-mm wide. Vertically, it tapered to a point 10-mm ahead of the shank at ground level and was relieved behind this point by a 40^{o} cut-away. This opener was designed to give some shattering effects, particularly in dry and firm soils, creating soil cracks near the row. The "U" shaped groove created by this opener had a surface width of approximately 40-mm. Unlike the triple

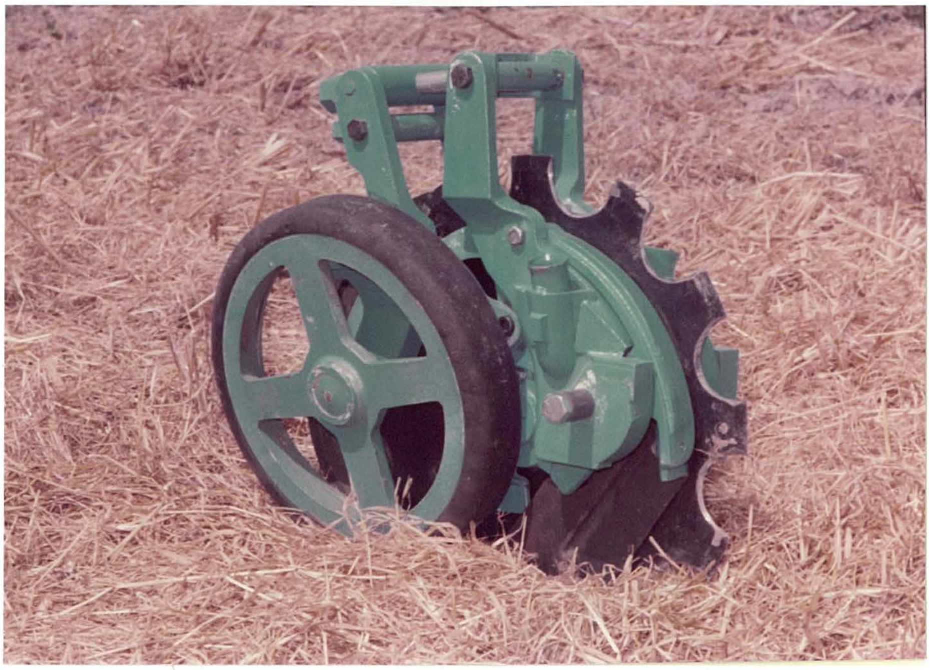


Figure 1: Front view of winged opener assembly.

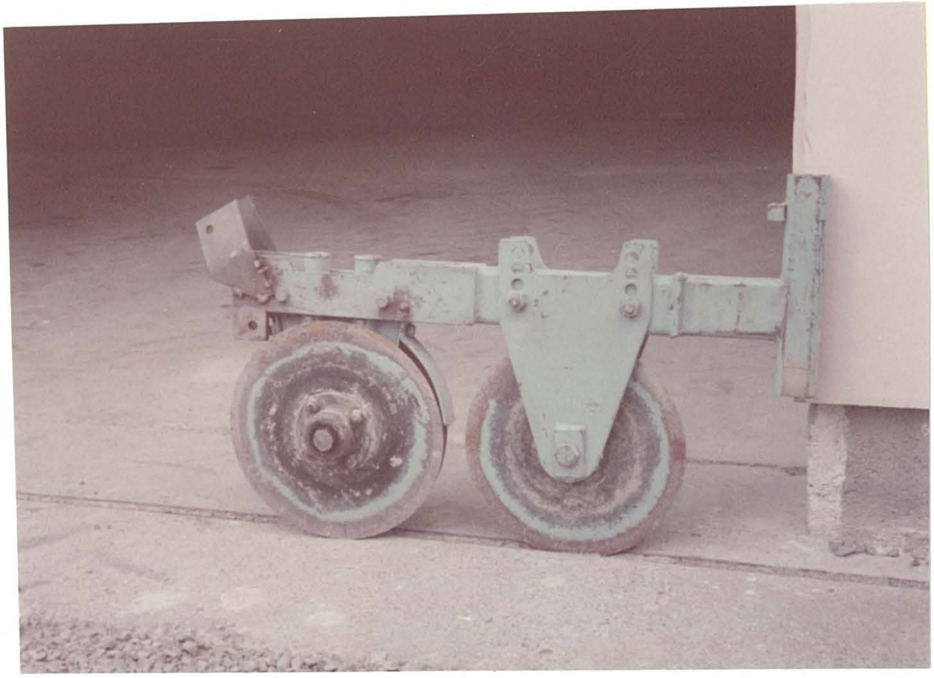


Figure 2: Side view of triple disc opener assembly.

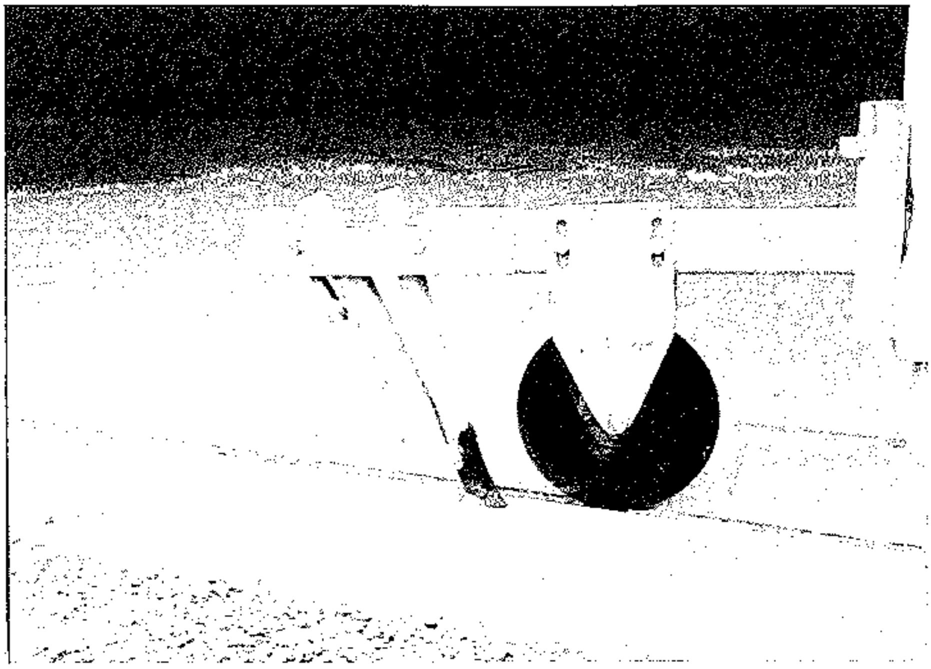


Figure 3: Side view of hoe opener assembly.

disc opener, no surface residue was pushed down into the groove, but instead was pushed bodily aside clear of the groove area.

(c) Experimental design:

The experimental design was a split-plot with three replicates, and is shown in Figure 4. Each plot was 0.45 m wide and 8 m long with a 2.6 m boundary between plots. Plots were split for irrigation and non-irrigation with a boundary of 7 m between treatments. With this arrangement any possible effect of wheel compaction on the experimental blocks was avoided as the tractor straddled each plot and operated on the 2.6 m boundary zone; and the drift onto non-irrigated areas (especially during windy days) was avoided by the 7 m boundary zone. During naturally rainy days irrigation was not applied.
On irrigated plots simulated rain of 20 mm a day with an intensity of 5 mm/hour was applied.

The drilling operations were performed 28 days after the first herbicide application. Three designs of openers (winged, triple disc and hoe), described above, were used, attached to a field experimental rig designed for this purpose. The seeder on the rig was calibrated for about 50 seeds of barley (Hordeum Vulgare, variety Magnum, with 96% laboratory germination) per meter of row with a 40 mm nominal depth of sowing.

(d) Data analysis:

In this experiment there were three plot-treatment factors, viz; irrigation, opener types and surface residue conditions. A standard "GENSTAT" programme for a "PRIME 750" computer was used to perform analyses of variance and to test the interactions of opener types and crop residue conditions, in terms of seed fate, oxygen diffusion rate (ODR), soil moisture and soil bulk density in the vicinity of the grooves .

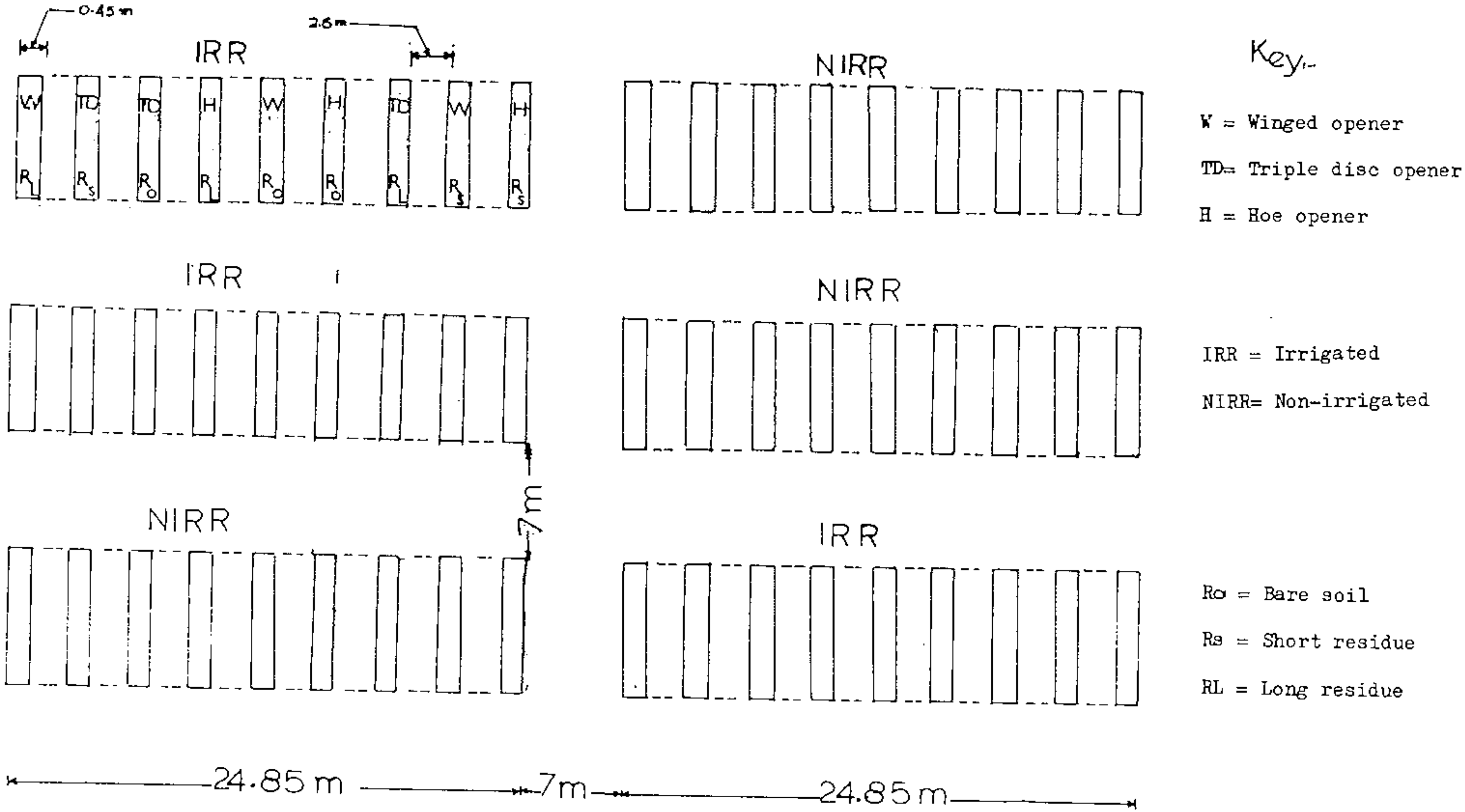


Figure 4: Experimental lay-out of field experiment (Experiment 1).

3.1.3 Measurements:

(a) Oxygen diffusion rates (ODR) in the vicinity of the grooves:

As described in Section 2 the platinum micro-electrode technique for measuring ODR *in situ* had been considered simple and economical compared with other methods (such as measuring soil porosity, using an "air picnometer" or a gas chromatographic technique) for measuring ODR. Thus, a platinum micro-electrode technique was used to measure ODR in the vicinity of the grooves created by direct drilling openers.

Principle of platinum micro-electrode technique:

Lemon and Erickson (1955) reported that the short length of platinum wire that formed the electrode (pushed longitudinally into the soil) simulated the geometry of a root passing through the aggregates. They felt that Fick's law of diffusion could be successfully applied to the calculation of the current obtained in the reduction of an electro-reducible material at a platinum surface. According to these authors, the "diffusion current" due to the reduction of oxygen at the platinum surface, was governed by the flux or the rate of oxygen diffusion to the surface of the electrode. The relationship between current and oxygen flux was given by McIntyre (1966) as follows:

$$f = i x m x 60 x 10^{-6} / nFA \quad g/cm^{2}/min.$$

where:

f= oxygen flux or oxygen diffusion rate.

i= current in micro-amperes.

m= molecular weight of oxygen (32 g/mole).

n= number of gram equivalent(s) per mole of oxygen (=4).

F= Faraday = 96,500 c/g- equivalent.

A= surface area of the electrode in contact with the soil surface, in square centimeters.

In this project, all the platinum micro-electrodes used were of uniform diameter (0.7 mm) and length (4.0 mm). The above cited relationship was used to convert current in micro-amperes into $gx10^{-8}/cm^{2}/min$, representing oxygen diffusion rate (ODR).

According to Hillel (1982), the method of measuring ODR with platinum micro-electrodes was not based on solution of the diffusion equation for definable boundary conditions, and the results did not provide a value for the effective diffusion coefficient for soil oxygen in the soil air or soil water. Rather, what was measured was a flux, which of course, depended on the size and shape of the electrodes and the location of their insertion, as well as on the diffusion coefficients of the surrounding porous media.

Thus the absolute values of ODR reported here are at best an approximation of what a root might experience. Nevertheless, as all openers and treatments were imposed in a common original soil matrix, using common electrodes, the measurements were felt to realistically reflect the relative oxygen diffusion rate (ODR) of the soil, as affected by the treatments imposed.

Calibration of platinum micro-electrodes:

The components required to measure ODR were a battery, variable resistor, voltmeter, ammeter, reference electrode and platinum electrode. The apparatus is shown in Figure 5.

This apparatus had three main functions:

To provide an external electric potential.
To measure the current in the external circuit connecting the two electrodes.
To apply a holding voltage to the other electrodes (if the instrument was designed to use more than one electrode).

The instrument circuit was in three main parts (Fig 5).

(1) Applied potential and measuring section.

Figure 5: Equipment for measuring oxygen diffusion rate (ODR).

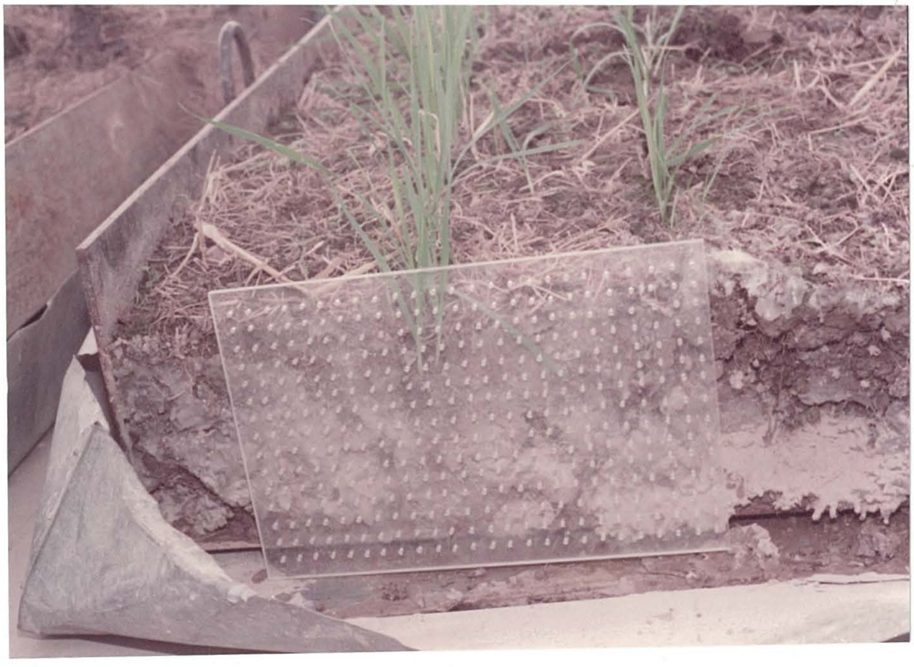


Figure 6: Extraction of samples for root studies with perspex pin-board.

(2) Electrode selector.

(3) Saturated silver-silver cloride electrode.

Despite care during construction, individual electrodes varied in the area of platinum wire which was exposed, which affected the current drawn-off. Electrode surfaces also contacted different films that impeded current flow. These variations were checked by using a calibration medium of standard oxygen-supplying capacity. For this purpose a 3 per cent suspension of sodium bentonite in 0.1 M sodium chloride was used. Prolonged agitation in a milk-shake mixer brought the bentonite into suspension. The formation of a uniform suspension was aided by sprinkling the bentonite gradually on the surface of the agitated solution in the milk shaker. The suspension was aerated by bubbling air through it for 5 minutes. The medium was then allowed to settle, convection currents being damped out by the viscosity of the bentonite.

A platinum electrode, held immovably in a retort stand, was inserted, and a reading of current was made after 5 minutes. Currents of approximately 3.5 micro-amperes at -0.65 V potential were usually obtained. All the electrodes were calibrated and compared in the same way.

Choice of potential:

Oxygen begins to reduce at a potential of about -0.2 volts. As the numerical negative potential is increased, current also increases.

Authors have differed in their views about the choice of potential. Birkle et al (1964) stated that any potential between -0.55 and -0.75 volts could be used. However, in several instances, particularly with 0.9 mm electrode, they found that the ODR departed from linearity at a potential of -0.8 volts, and -0.75 V might be too close to that point of departure. They suggested measuring as high a current as possible for a given soil oxygen status, if the currents involved were already low. These authors also observed that with low currents, the increase in amperage with increase in potential was also low. Stolzy and Letey (1964) had published results of measurements made at -0.65 V. Since no compelling reason existed for using any other potential, Birkle et al (loc.cit) also recommended -0.65 V for measuring oxygen diffusion rate.

In all the experiments reported here a potential of -0.65 volts was chosen. All the electrodes were also calibrated in sodium bentonite suspension at this potential.

Procedure for ODR measurements in the vicinity of the grooves:

1. At the start of a series of measurements, the anode and bridge, which were normally kept dry, were filled with a saturated solution of potassium chloride.
2. Electrical connections, which were left open between measurements, were then closed, (i.e. the connections to the anode and that from the positive end of the battery to the rheostat).
3. The rheostat was adjusted to apply a potential of -0.65 V to the cathode. Care was taken to maintain this -0.65 V constant throughout the experimental period while making ODR measurements.
4. The platinum electrode was pushed into the soil to the required depth. It has been recommended that the distance between an electrode and ceramic tip should not be more than 2.5 m (Birkle et al, 1964). Therefore, the ceramic tip was inserted into the soil at a distance of approximately 0.5 m from an electrode. When the ceramic tip of the anode bridge was pressed against the soil surface a large initial surge of current occurred as oxygen near the platinum surface was reduced. Contact of the ceramic tip with the soil surface was maintained and the current began to fall, becomming constant in 4-5 minutes.
5. Five minutes after closing of the circuit, the micro-ampere meter was gently tapped to ensure that the mechanical movement of the meter had equilibrated, and the current recorded.
6. Any mechanical vibration or movement of the platinum

electrode during the 5 minute flow of current, might cause an upsurge of current, and this would bring the platinum closer to the region of unreduced oxygen (Birkle et al, 1964). Such movements, therefore, were avoided.

7. Oxygen diffusion rate (ODR) measurements were taken at the centre of the grooves by inserting platinum micro-electrodes 5 mm below the centre of the grooves. Oxygen diffusion rate measurements were taken only from the irrigated conditions, on days 0, 10 and 21.
8. "Poisoning" of the electrodes (probably from a chemical deposit that changes electrode reaction) may occur if the electrodes were left in the soil for more than a week. A "poisoned" electrode may give a faulty reading (Birkle et al,loc cit). Therefore, after taking the measurements, the electrodes were immediately removed from the soil and washed in clean water.
9. Soil factors such as temperature, concentration of salts and electrical conductivity may affect ODR measurements. In this project only relative values of ODR (as affected by the treatments imposed on a common soil) were measured. Thus no attempt was made to measure soil temperature, salt concentration or electrical conductivity of the soil around the groove profiles, in order to express absolute values of ODR.
10. Calibration of each electrode was undertaken before taking ODR measurements on each measuring day.

(b) Soil bulk density:

Soil bulk density is the most widely accepted measure of compaction. Within a given soil, the bulk density provides a measure of the packing condition of soils but does not yield any information about the arrangement of soil particles. However, if the specific gravity of the soil grains is known, then bulk density values can also be used to devise a measure of porosity or void ratio (Gradwell, 1974).

A major difficulty in determining soil bulk density is the measurement of volume occupied by solids. Various methods have been suggested and used, but each method appeared to be applicable to a specific situation and for a certain objective (Stace and Palm, 1962). In direct drilling experiments a piston type core sampler had been used by Choudhary (1979). This author used a core sampler with a 15 mm effective length and 6.25 mm diameter. A similar sampler was used by Mai (1978) with effective length of 13 mm and 11 mm diameter. Both of these authors had reported that Willardson and Taylor had found that small diameter samples were as accurate as large diameter samples, and the variance associated with the smaller cores was low enough for most uses. In a pilot experiment, Mai (loc.cit) compared two samples of 11 mm and 52 mm diameters with effective lengths of 13 mm and 33 mm respectively, and found no significant difference in measurements of soil moisture or soil bulk density.

In the experiment reported here a similar soil sampler to that used by Mai (loc.cit) was used. The same soil samples collected for soil moisture measurements were also used for soil bulk density measurements as a means of indirectly representing soil ODR measurements. The soil bulk density measurements were taken only from the irrigated conditions on day 21.

(c) Soil moisture content:

Soil water deals with three aspects: surface retention, infiltration and soil moisture (Blake, 1973). "The accurate measurements of the soil moisture potential near to the soil surface/atmospheric interface has been a frustrating exercise because of continuity of liquid and gaseous water fluxes" (Painter, 1976). Measurements of the soil moisture status close to the groove in this study were considered to involve problems associated with near surface measurements because of the proximity of both the drilled groove (which was sometimes open to the atmosphere) and the true soil surface. Noble (1973) suggested that the techniques for measuring soil water could be grouped under the folowing main headings:

1. Those which measured soil water directly.
2. Those which measured soil water indirectly.
3. Those which involved destructive sampling of the soil at the experimental site.

4. Those which did not involve destructive sampling.

Of these, the long established destructive gravimetric procedure is the only one which comes close to category (1), although the neutron technique might also be included. Virtually all techniques which measure electrical, thermal, or acoustic properties of the soil or sensors come within category (2). Techniques measuring potentials were separated from this group because they measured parameters directly associated with moisture status and its importance to soil plant association (Noble, loc cit). Painter (loc.cit) reported that tensiometers were not useful for the determination of soil moisture near the surface, because tensiometers broke down at -9 J/kg or below. A neutron probe caused problems because of limits in the sampling volume, which was affected by the steep gradients in soil moisture near the surface. For similar reasons, other methods such as gamma ray absorption, thermal methods and electrical capacitance were considered not to be useful tools for measuring moisture levels near to the surface.

Choudhary (1979) considered and tested psycho-meters, electrical resistance blocks, gypsum beads, glass paper and direct thermo-gravimetric methods for measuring moisture content of soil immediately adjacent to and within direct drilled grooves. He concluded that a direct gravimetric method for measuring soil moisture was simple and reliable. The usefulness and reliability of this method had already been reported by several authors (Painter, loc.cit; Holmes et al, 1967). This method had been widely used by a number of authors in direct drilling experiments. (Mai, 1978; Lal, 1976; Afzal, 1981; Follas, 1982).

The experiment reported commenced at initial soil moisture contents of 22.5% (d.b) in "bare soil" and "short residue" conditions and 26.0% (d.b) in "long residue" conditions. A thermo-gravimetric method was used for soil moisture measurements. These measurements were taken only at the centre of the grooves and only from the irrigated conditions, on day 21. The soil samples collected for soil bulk density measurements were also used for soil moisture measurements.

(d) Seed and seedling performance:

The response of seeds to the imposed soil-climate-machine interactions was measured in terms of seedling emergence, sub-surface seed fate and plant growth. Barley was used in all experiments because of its economic importance and tolerance to temperature variations. Seeds were considered to have emerged when they appeared above the horizontal plane of the ground surface, regardless of whether or not they could be seen in an open groove below this arbitrary plane.

Final individual seed fate counts, (as originally explained by Baker (1976) and later used by Choudhary (1979)) were determined after day 21. The purpose of this was to classify seedlings that had failed to emerge as "germinated but unemerged" or "ungerminated/dead".

In these experiments the ungerminated seeds and/or unemerged seedlings were counted by separating them from soil removed with a 300-mm long semi-cylindrical hand scoop. These counts were added to the total pool which included emerged seedlings. Each treatment within an experiment was represented by a sample of approximately 50 seeds (variety Magnum) of 96% laboratory germination. From day 5 when the seedlings usually started emerging, daily counts of emergence were taken until the count of total emergence had stabilized which usually occurred by day 21.

(e) Root/shoot weights:

Extraction of samples for root studies, from both field and bin soils, used shovels, spades, sharp knives and pinboards. The pinboard technique was found time consuming and difficult to use, but had been recommended by Dixon (1972), Mai (1978) and J. Springett (pers comm, 1983). A pinboard of 5 mm thick perspex, measuring 200 mm x 300 mm with pin holes arranged in a square pattern 10 mm apart, was used (Figure 6). When sampling, care was taken to avoid disturbance of adjacent seedlings. Samples were soaked in gently-flowing tap water for 24 hours, after which the remaining soil was separated from the roots by a hand-held, fine low pressure jet of water.

Care was taken to minimise the loss of fine root material during washing.

On day 21, root dry matter weights were determined using the pinboard technique. By that time it was felt that a reasonable record of seedling emergence, vigour and growth could be made by harvesting and weighing seedlings. The dry matter weights of roots were measured after drying in an oven at 80^{o} C for 24 hours. Shoots were cut from the roots and their respective dry weights were measured separately.

3.1.4 <u>Limitations</u>:

(a) In the field experiment, no control was possible over maximum precipitation, because of unpredictable climatic conditions, which also affected ambient temperatures. Variation in soil temperature at 100 mm depth and ambient temperature during the month of December and January is shown in Appendix 2a.

(b) The capacity of the ODR meter which was available for this experiment, restricted measurements to two at a time. This restricted the data available for this parameter.

(c) The non-irrigated plots could not be relied on to remain dry, because of natural weather changes. However, the rainfall data (Appendix 2b) for the month of December and January showed that the experimental period remained without substantial rain (except for three days), and thus maintained a contrast between the soil moisture content of irrigated and non-irrigated conditions.

Unless specifically described, the materials and methods adopted in this experiment also related to all subsequent experiments in this project.

3.1.5 Results and discussion (Field experiment):

(a) Seedling emergence:

Table 1 shows the effects of contrasting irrigation conditions, opener types and contrasting crop residue on seedling emergence, and the interactions amongst these parameters. It appears from the Table, that contrasting irrigation conditions had a highly significant ($P<0.01$) effect on percentage seedling emergence. The non-irrigated (78.9%) plots showed significantly larger numbers of emerged seedlings than the irrigated conditions (46.0%).

Opener types had a significant ($P<0.05$) effect on percentage seedling emergence. The triple disc opener (55.7%) showed a significantly lower seedling emergence percentage than the winged (68.8%) and hoe (62.8%) openers, which were not significantly different.

The contrasting crop residue conditions had a highly significant ($P<0.01$) effect on percentage seedling emergence counts. The "long residue" (68.9%) showed a significantly larger number of emerged seedlings than the "short residue" (57.3%) and "bare soil" (61.1%) which were not significantly different.

The interactions amongst contrasting irrigation conditions, opener types and contrasting crop residue conditions confirmed the generally lower emergence counts under the irrigated conditions compared to the non-irrigated conditions, although the winged and hoe openers in "long residue" under irrigation recorded reasonable emergence counts of 75% and 67.7% respectively. In fact the only treatment which was superior to the winged opener in residue was the same treatment in the absence of irrigation.

The triple disc opener was observed to push residue inside the groove while the winged opener kept residue over the groove and the hoe opener swept residue aside. Emergence from the triple disc grooves under both irrigated and non-irrigated conditions improved slightly as the amount of residue was reduced while in the winged and hoe opener grooves (at least

Table 1: Effects of contrasting soil moisture conditions,direct drilling opener types and contrasting crop residue conditions, on the fate of direct drilled barley seeds.

Treatments/ Seed fate	Irrigation		Openers			Residue			Interactions				
	Non-Irr	Irr	Winged	Triple disc	Hoe	Bare	Short	Long	Openers/ Irrigation/ Residue	Winged	Triple disc	Hoe	
Seedling emergence (%)	78.9 Aa	46.0 Bb	68.8 Aa	55.7 Bb	62.8 Aa	61.1 Bb	57.3 Bb	68.9 Aa	Non-Irr				
									Bare	81.7	82.0	75.7	
									Short	75.7	84.0	70.0	
									Long	90.0	64.7	86.0	
									Irr				SED1=6.03
									Bare	47.0	38.3	41.7	SED2=4.62
									Short	43.3	35.0	35.7	SED3=5.89
									Long	75.0	30.0	67.7	
Ungerminated or dead seeds (%)	9.7 Bb	26.3 Aa	12.7 Bb	25.3 Aa	16.0 Bb	18.2 Aa	20.1 Aa	15.9 Ab	Non-Irr				
									Bare	7.7	8.0	11.0	
									Short	10.0	7.7	13.3	
									Long	3.0	22.0	4.3	
									Irr				SED1=3.63
									Bare	22.3	35.0	25.0	SED2=3.08
									Short	25.0	36.7	27.7	SED3=3.72
									Long	8.3	42.3	14.7	
Germinated but unemerged seedlings (%)	11.5 Bb	27.6 Aa	18.4 Aa	19.1 Aa	21.2 Aa	20.7 Aa	22.7 Aa	15.3 Bb	Non-Irr				
									Bare	10.7	10.0	13.3	
									Short	14.3	8.7	16.7	
									Long	7.0	13.3	9.7	
									Irr				SED1=4.11
									Bare	30.0	26.7	33.3	SED2=3.15
									Short	31.7	28.3	36.7	SED3=3.89
									Long	16.7	27.3	17.7	

Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case, $P<0.05$).
SED1=Standard error of difference within irrigation types.
SED2=Standard error of opener and irrigation interactive differences.
SED3=Standard error of all other interactive differences.

under irrigation) there was a marked decline in seedling emergence when the amount of the residue was reduced. Perhaps the lower emergence in the grooves of the triple disc opener in "long residue" under irrigated conditions might have been due to adverse phytotoxic effects of the decomposing crop residue inside the groove, as reported by Ellis et al (1975); Lynch (1977, 1978) and Lynch et al (1980).

Figures 7 and 8 show the rates of seedling emergence under irrigated and non-irrigated conditions respectively. Figure 8 shows that under non-irrigated conditions all the curves followed similar shapes and plateaued at day 13. However, under irrigated conditions (Figure 7) plateauing in all treatments was extended to day 15. This probably reflected the less-than-optimal conditions resulting from excessive moisture which slowed down seed germination and seedling growth. Both sets of curves also illustrate that under both non-irrigated and irrigated conditions the winged and hoe openers benefitted from the presence of "long residue" compared to the triple disc opener which in both soil moisture conditions showed the lowest rate of percentage seedling emergence in "long residue".

(b) Ungerminated/dead seeds.

Table 1 also shows the effects of contrasting irrigation conditions, opener types and crop residue conditions on ungerminated/dead seeds, and the interactions amongst these parameters. From the Table, it appears that the non-irrigated conditions showed significantly ($P<0.01$) lower numbers of ungerminated/dead (9.7%) seeds than the irrigated conditions (26.3%).

The opener types had a significant ($P<0.05$) effect on ungerminated/dead seeds. The grooves of the triple disc opener showed a significantly larger number of ungerminated/dead seeds (25.3%) than the grooves of both the winged (12.7%) and hoe (16.0%) openers, which were not significantly different.

The contrasting crop residue conditions had a significant ($P<0.05$) effect on percentage of ungerminated/dead seeds. The "long residue" showed a significantly lower number of ungerminated/dead seeds (15.9%) than either the "short residue" (20.1%) or "bare soil" (18.2%), which were not significantly different.

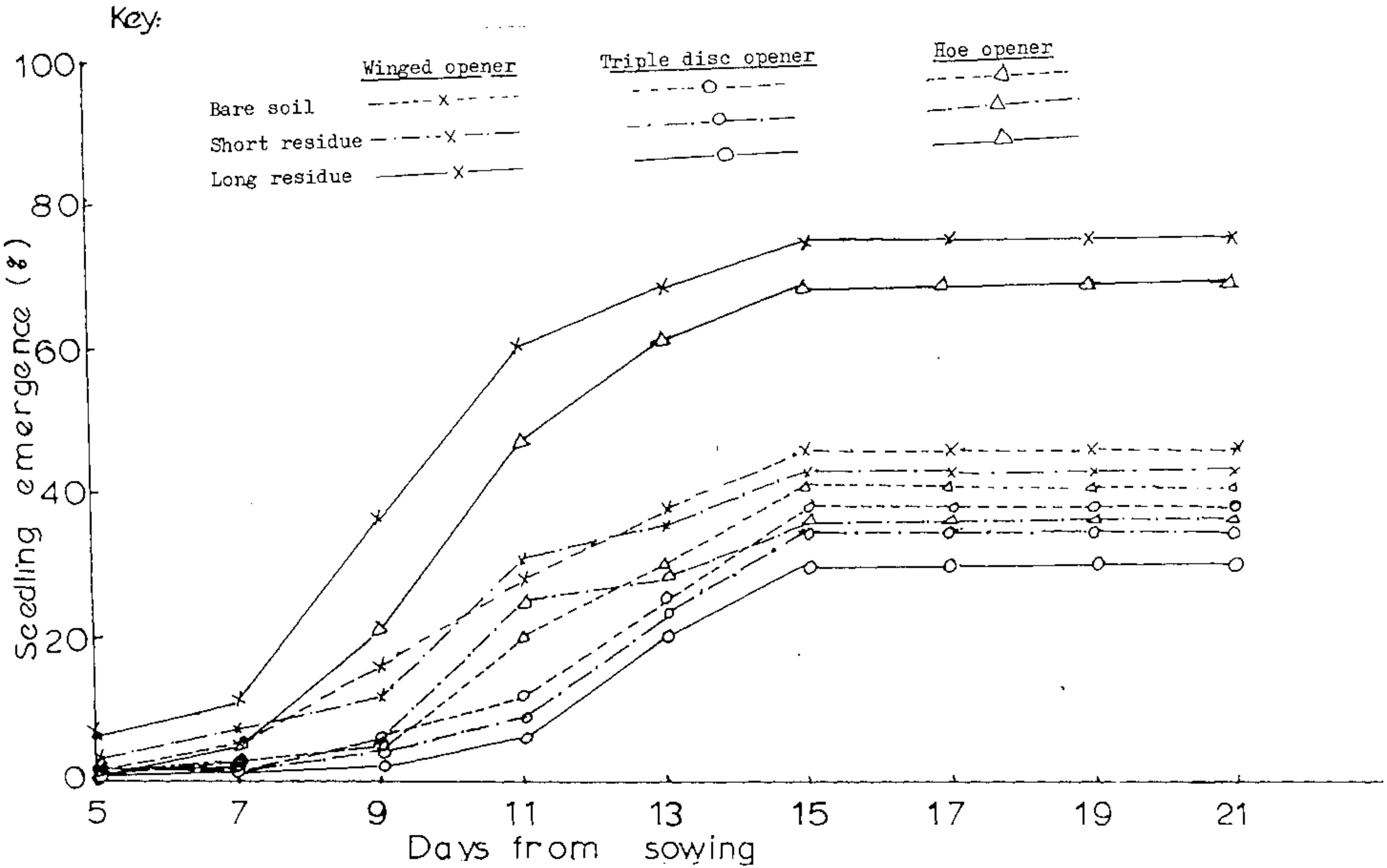


Figure 7: Effects of direct drilling opener types and contrasting crop residue conditions on rates of seedling emergence of barley in an irrigated soil.

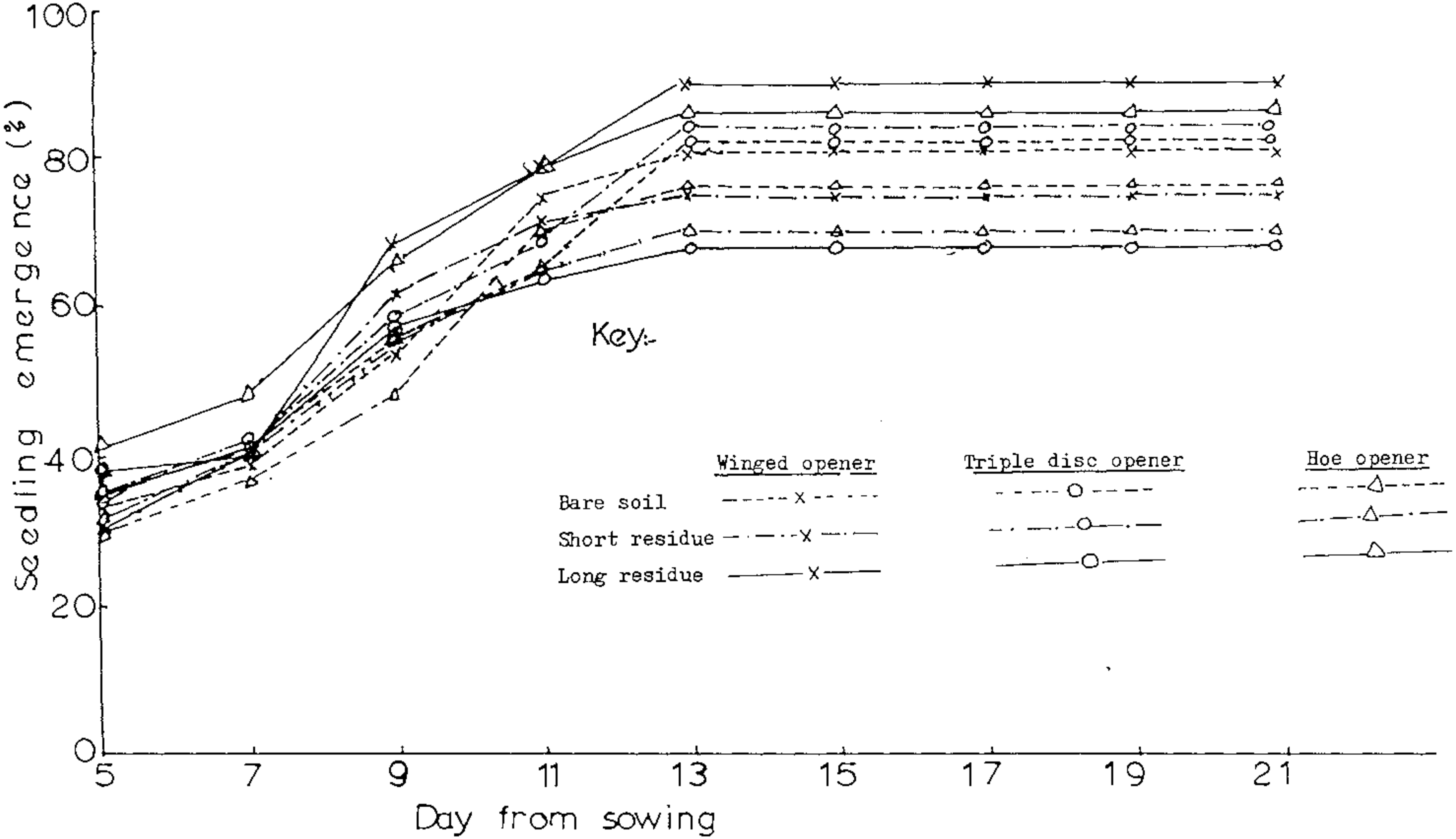


Figure 8: Effects of direct drilling opener types and contrasting crop residue conditions on rates of seedling emergence of barley in a non-irrigated soil.

The interactions showed a generally lower number of ungerminated/dead seeds under non-irrigated conditions than under irrigated conditions. Under irrigated conditions the "long residue" appeared to favour the winged and hoe openers, while it disadvantaged the triple disc opener, which showed the largest number of ungerminated/dead seeds of all opener types in "long residue". The numbers of ungerminated/dead seeds in the grooves of the triple disc opener under "long residue" and non-irrigated conditions were little different than those in the grooves of the winged and hoe openers in irrigated "bare soil" and "short residue" conditions. This might suggest that with the triple disc opener, the presence of "long residue" was more important than irrigation.

(c) "Germinated but unemerged" seedlings

Table 1 also lists the effects of contrasting irrigation conditions, opener types and crop residue conditions on "germinated but unemerged" seedlings, and the interactions amongst these parameters. The non-irrigated grooves showed a significantly ($P<0.01$) lower number of "germinated but unemerged" seedlings (11.5%) than the irrigated conditions (27.6%).

Opener types had no significant effects on the percentages of "germinated but unemerged" seedlings.

The contrasting crop residue conditions had a highly significant ($P<0.01$) effect on "germinated but unemerged" seedlings. The "long residue" showed a significantly lower number of "germinated but unemerged" seedlings (15.3%) than the "short residue" (22.7%) and "bare soil" (20.7%), which were not significantly different.

The interactions showed a consistent trend with each opener and residue treatment towards lower numbers of "germinated but unemerged" seedlings in non-irrigated conditions than in irrigated conditions. Under irrigation the "long residue" again appeared to favour the winged and hoe openers while with the triple disc opener it had little effect. However, in "short residue" and "bare soil" conditions there appeared to be little difference between any of the openers.

Summary of seed fate:

Figure 9 shows the collective data of seed fate. The Figure illustrates that the major problem with the triple disc opener was ungerminated/dead seeds, especially in "long residue", both under non-irrigated and irrigated conditions. Most other openers in all conditions had "germinated but unemerged" seedlings as their largest problem. The Figure also illustrates that the highest maximum seedling emergence was obtained by using the winged and hoe openers in "long residue" under both non-irrigated and irrigated conditions.

(d) Dry matter weight of roots:

Table 2 shows the effects of contrasting irrigation regimes, opener types and crop residue conditions, on root weights per plant, and the interactions amongst these parameters. From the Table, it appears that irrigated conditions (24.3 mg) showed significantly ($P<0.01$) lower dry matter root weights per plant than non-irrigated conditions (46.5 mg).

The opener types had a significant ($P<0.05$) effect on dry matter root weights per plant. The grooves of the winged opener showed significantly ($P<0.05$) higher root weights (41.7 mg) than the grooves of the triple disc opener (29.5 mg), but this latter opener was not significantly different than the hoe opener (35.0 mg), which was also not significantly different from the winged opener.

The contrasting crop residue conditions had a highly significant ($P<0.01$) effect on dry matter root weights per plant. The "long residue" showed significantly higher root weights (44.5 mg) than both the "short residue" (33.1 mg) and "bare soil" (28.6 mg), which were not significantly different.

The interactions amongst the three parameters discussed above, showed that most of the non-irrigated plots recorded higher root weights than under the irrigated conditions. The most notable effect was that hoe opener in "long residue" was unaffected by irrigation. Under irrigated conditions the most notable advantage with any of the treatment combinations was with the winged and hoe openers in "long residue" compared with all other opener/residue combinations. Perhaps the poor performance of the triple

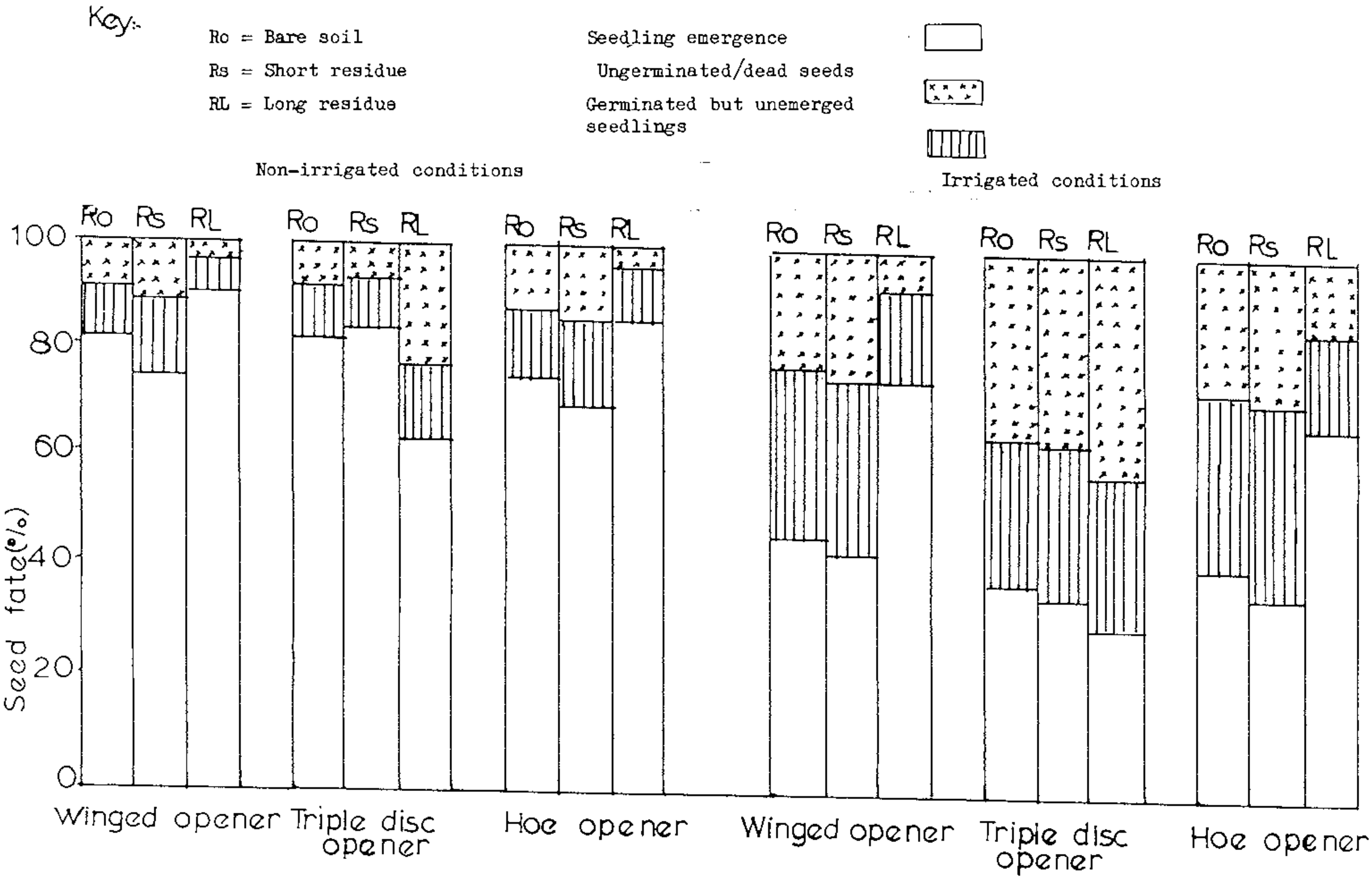


Figure 9: Effects of opener types and contrasting crop residue conditions on **cumulative** seed fate of direct drilled barley, in irrigated and non-irrigated conditions.

Table 2: Effects of contrasting soil moisture conditions, direct drilling opener types and contrasting crop residue conditions, on the root/shoot weights of direct drilled barley seeds.

Treatments/ Root and shoot weights	Irrigation: Non-Irr	Irrigation: Irr	Openers: Winged	Openers: Triple disc	Openers: Hoe	Residue: Bare	Residue: Short	Residue: Long	Interactions: Openers/ Irrigation/ Residue	Winged	Triple disc	Hoe	
Root weight (mg)	46.5 Aa	24.3 Bb	41.7 Aa	29.5 Ab	35.0 Aab	28.6 Bb	33.1 Bb	44.5 Aa	Non-Irr				
									Bare	44.6	38.3	36.0	
									Short	56.0	52.3	33.6	
									Long	64.3	41.3	52.3	
									Irr				SED1=6.50
									Bare	19.0	16.0	17.6	SED2=5.87
									Short	19.0	18.6	19.3	SED3=7.61
									Long	47.3	10.3	51.3	
Shoot weight (mg)	384 Aa	198 Bb	307 Aa	284 Aa	281 Aa	246 Bc	283 Bb	343 Aa	Non-Irr				
									Bare	306	351	307	
									Short	389	401	317	
									Long	486	440	457	
									Irr				
									Bare	183	147	182	SED1=37.5
									Short	192	205	194	SED2=31.7
									Long	286	158	228	SED3=38.9

Unlike letters in a row denote significant differences (upper case, P<0.01; Lower case, P<0.05).
SED1=Standard error of difference within irrigation types.
SED2=Standard error of opener and irrigation interactive differences.
SED3=Standard error of all other interactive differences.

disc opener in "long residue" under irrigation resulted from the effects of decomposing crop residue pushed into the grooves under the wet soil conditions (Ellis et al, 1975; Lynch, 1977, 1978; and Lynch et al, 1980).

(e) Dry matter weight of shoots:

Table 2 also lists the effects of contrasting irrigation regimes, opener types and crop residue conditions, on dry matter weights of shoots per plant, and the interactions amongst these parameters. From the Table, it appears that there was a highly significant ($P<0.01$) effect of contrasting irrigation conditions on shoot weights per plant. The irrigated conditions showed significantly ($P<0.01$) lower shoot weights (198 mg) compared to the non-irrigated conditions (384 mg).

Surprisingly, opener types had no significant effects on dry matter shoot weights per plant. However, the contrasting crop residue conditions had significant ($P<0.05$) effects on shoot weight. The "long residue" showed significantly higher shoot weights (343 mg) than the "short residue" (283 mg), which itself was significantly higher than the "bare soil" (246 mg).

The interactions amongst contrasting soil moisture regimes, opener types and crop residue conditions showed consistently higher shoot weights for opener/residue combinations under non-irrigated conditions than under irrigated conditions. The triple disc opener in "long residue" under irrigated conditions showed slightly lower shoot weights compared with the winged and hoe openers in these conditions, but there were no such differences with other residue lengths in irrigated conditions, nor with most of the residue lengths under non-irrigated conditions. In fact in "short residue" in the latter soil conditions, the hoe opener promoted less shoot weight than the triple disc opener.

(f) Oxygen diffusion rates (ODR) at the centre of the grooves:

Table 3 lists the effects of opener types and contrasting surface residue conditions, on ODR at the centre of the groove, in the irrigated soil, and the interactions between these parameters. It appears from the Table that on day 0 opener types and the contrasting crop residue conditions had no significant effects on ODR values at the centre of the grooves.

Table 3: Effects of direct drilling opener types and contrasting crop residue conditions, on oxygen diffusion rate at the centre of the grooves, under irrigated conditions.

Days from sowing	Openers			Residue			Interactions				
	Winged	Triple disc	Hoe	Bare	Short	Long	Openers/ Residue	Winged	Triple disc	Hoe	
	ODR $(g \times 10^{-8}/cm^2/min)$										
							Bare	40.2	48.3	38.8	
0	43.2 Aa	44.8 Aa	41.2 Aa	42.4 Aa	43.1 Aa	43.7 Aa	Short	42.3	46.3	40.5	SED1=3.21
							Long	47.0	39.8	44.3	SED2=3.58
							Bare	15.3	11.7	14.5	
10	18.4 Aa	12.9 Ba	17.6 Aa	13.8 Bb	14.7 Bb	20.4 Aa	Short	16.2	12.0	16.0	SED1=1.54
							Long	23.8	15.0	22.3	SED2=1.61
							Bare	14.8	12.0	13.7	
21	17.4 Aa	13.4 Bb	17.1 Aa	13.5 Bb	14.4 Bb	19.9 Aa	Short	14.5	14.2	14.7	SED1=1.37
							Long	22.8	14.0	22.8	SED2=1.53

Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case, $P<0.05$).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences..

However, on days 10 and 21, the grooves of the triple disc opener recorded significantly ($P<0.01$) lower ODR values compared with the grooves of the winged and hoe openers, which were not significantly different.

On day 0 there appeared to be no significant effects of contrasting crop residue conditions on ODR values. However, on days 10 and 21 the "long residue" showed significantly ($P<0.01$) higher ODR values compared with the "short residue" and "bare soil", which were not significantly different.

The interactions between opener types and crop residue conditions showed an increase in ODR when "long residue" replaced "bare soil" for the winged opener and a corresponding decrease for the triple disc opener on day 0. On day 10 "long residue" appeared to favour all openers, while on day 21 only the winged and hoe openers benefitted by the presence of "long residue".

Figure 10 shows the changes in ODR values at the centre of the grooves in irrigated plots with time. There was a rapid reduction in ODR values in all grooves and residue conditions between days 0 and 10, although the ODR values in the triple disc opener grooves declined more than in the grooves of the winged and hoe openers. Between days 10 and 21 the ODR values at the centre of the grooves of the winged and hoe openers either remained constant or declined slightly. Under "short residue" and "bare soil" the ODR values in the triple disc opener grooves increased slightly between days 10 and 21. No logical explanation could be given for this latter effect. The Figure also illustrates that with the winged and hoe openers under "long residue" conditions, the ODR values between days 10 and 21 were higher than all other treatments.

(g) Soil bulk density at the centre of the grooves:

Table 4 shows the effects of opener types and contrasting crop residue conditions, on soil bulk density in the irrigated soil, and the interactins between these parameters. It appears from the Table, that as with ODR, openers had a highly significant ($P<0.01$) effect on soil bulk density at the centre of the grooves. The triple disc opener groove showed a significantly higher soil bulk density value (1.32 g/cm^3) than the grooves of the winged (1.17 g/cm^3) and hoe (1.15 g/cm^3) openers, which were not significantly

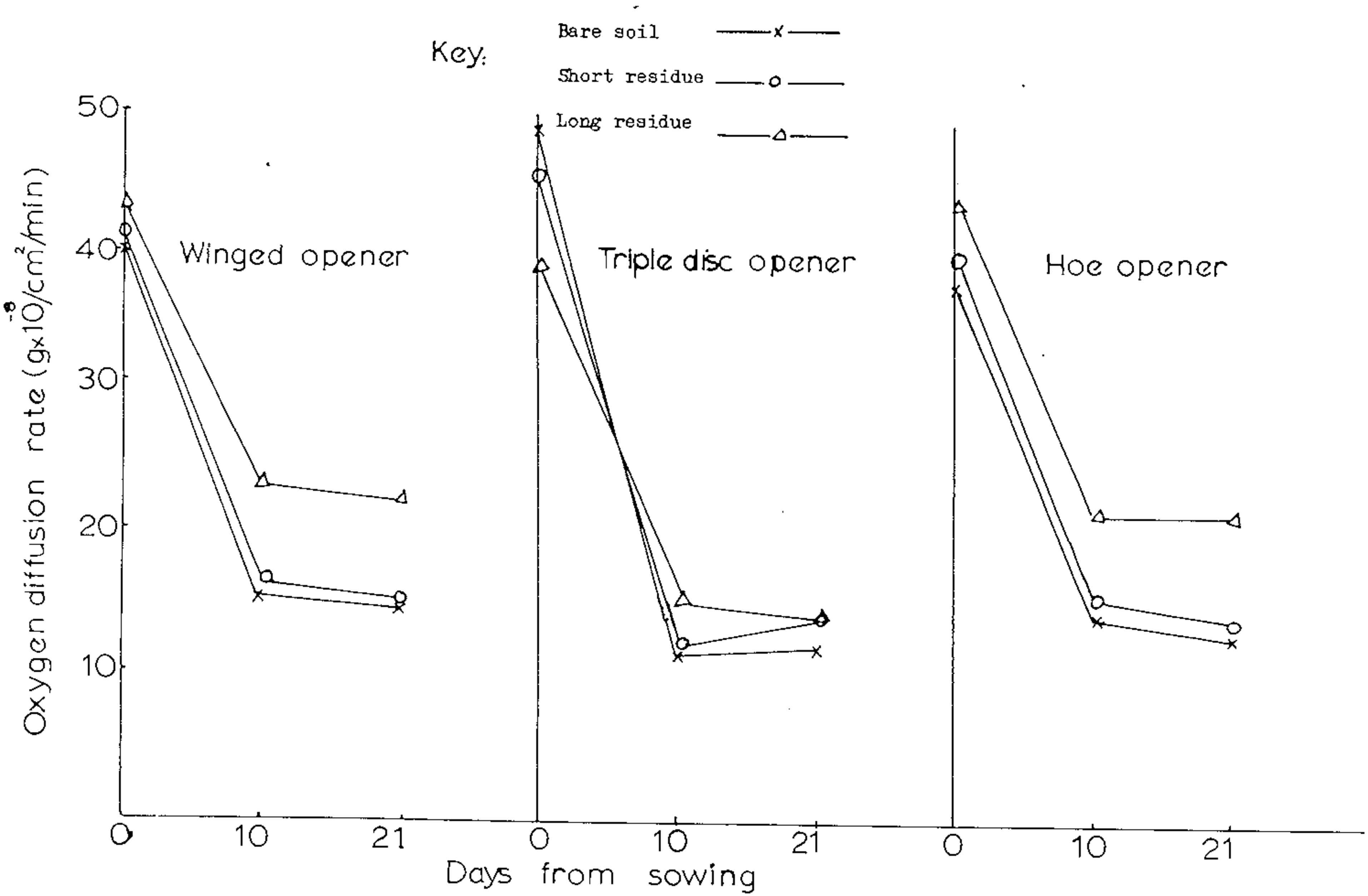


Figure 10: Effects of direct drilling opener types and crop residue conditions on changes in oxygen diffusion rate (ODR) with time, in an irrigated soil.

Table 4: Effects of direct drilling opener types and contrasting crop residue conditions, on soil bulk density and soil moisture content, at the centre of the grooves, under irrigated conditions.

	Openers			Residue			Interactions				
	Winged	Triple disc	Hoe	Bare	Short	Long	Openers/ Residue	Winged	Triple disc	Hoe	
Soil bulk density (g/cm^3)	1.17 Bb	1.32 Aa	1.15 Bb	1.26 Aa	1.25 Aa	1.12 Bb	Bare	1.22	1.31	1.23	
							Short	1.23	1.30	1.22	SED1=0.052
							Long	1.05	1.34	0.98	SED2=0.059
Soil moisture content (% d.b)	30.4 Ab	33.7 Aa	31.4 Ab	32.5 Aa	31.9 Aa	31.2 Aa	Bare	31.3	33.5	32.6	
							Short	30.8	33.1	31.7	SED1=1.64
							Long	29.2	34.5	29.9	SED2=1.79

Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case, $P<0.05$).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

different.

The contrasting crop residue conditions had a highly significant effect ($P<0.01$) on mean soil bulk densities across all opener types. The "long residue" had a significantly lower soil bulk density (1.12 g/cm^3) compared to "short residue" (1.25 g/cm^3) and "bare soil" (1.26 g/cm^3) conditions, which were not significantly different.

The interactions between opener types and crop residue conditions indicated that the "long residue" compared with "short residue" and "bare soil" favoured the winged and hoe openers but had no effect on the triple disc opener. Bulk density levels in the "long residue" variant of the triple disc opener appeared to be higher than the corresponding variant of the winged and hoe openers.

(h) Soil moisture content at the centre of the grooves:

Table 4 also shows the effects of opener types and contrasting crop residue conditions on soil moisture contents (%d.b.) in the irrigated soil, and the interactions between these parameters. It appears from the Table, that opener types had a significant ($P<0.05$) effect on percentage soil moisture content at the centre of the grooves. The grooves of triple disc opener showed a significantly higher soil moisture content (33.7% d.b) than the grooves of the winged (30.4% d.b) and hoe (31.4% d.b) openers, which were not significantly different.

The contrasting surface residue conditions had no significant effects on the moisture content at the bases of the grooves.

The interactions showed that in "long residue" the grooves of the triple disc opener were slightly wetter than the grooves of the winged and hoe openers.

3.1.6 Discussion of experiment (Field experiment)

It is clear from the results of the field experiment, that under non-irrigated conditions opener types and contrasting surface residue conditions had significant effects on seed germination and seedling growth. Despite changing weather conditions in the field, it appeared that "long residue", both in irrigated and non-irrigated conditions, benefitted those opener types which did not either cause compaction or push the residue into the grooves in contact with the seed. In this respect, the triple disc opener was observed to push residue into the grooves and was known to cause compaction (Mai, 1978), while the winged opener retained the residue over the grooves and the hoe opener swept it aside.

There was a total natural rainfall of approximately 105.5 mm during the 21 days of the experimental period, of which approximately 60 mm fell on two consecutive days (4 and 5) (Appendix 2b). Thus the non-irrigated plots were also very wet for a period, which might have resulted in some decomposition of the crop residue. Therefore, even under non-irrigated conditions, the poor performance of the grooves of the triple disc opener in "long residue" might be attributed to the adverse effects of the decomposing residue inside the groove of this opener. On the other hand, under non-irrigated conditions, the performance of the grooves of this opener in terms of seedling emergence, appeared to be marginally superior to the winged and hoe openers, both under "bare soil" and "short residue" conditions.

Several authors (Baker, 1976; Mai, loc cit, Choudhary and Baker, 1980; and Choudhary and Baker, 1982) have reported that the biological performance of triple disc opener grooves was more sensitive to soil moisture in both moist and dry conditions than the grooves of the winged or hoe openers. They felt that the performance of the grooves of the triple disc opener was strongly affected by changes in soil moisture and ambient conditions, and was at greater risk in dry conditions than grooves created by winged or hoe openers. According to Mai (loc cit), the triple disc opener groove could be expected to have a higher soil compaction and smear at the sides and base of the groove compared to the groove created by the winged opener. He found that this had a marked effect on lupin root development, and in some instances caused distortion and deflection. This author also claimed to have counted a lower number of earthworms around the groove profile of the triple disc opener compared to the grooves of the winged opener, but he was unable to suggest any possible reason for this.

From a review of the literature (Section 2), it appears possible that in the present experiment the low ODR values at the centre of the grooves of the triple disc opener under irrigated conditions might have been the result of soil compaction at the sides and base of this groove, which apparently did not occur in the grooves of the winged and hoe openers. Mai (loc cit) had tested only the winged opener in this respect, but Dixon (1972) included all three openers in his tests. Perhaps earthworm populations and their activity might have responded to the groove profile of the triple disc opener, which did not promote a high ODR at the centre of this groove. It appears from ODR data that after day 0 a decline in ODR might have been partialy because of irrigation.

It seemed logical to study ODR regimes around the groove profiles of direct drilling openers together with earthworm populations in the presence and absence of crop residue. In the field experiment the changing weather conditions also made it difficult to define clearly the effects of treatment factors on seed germination and seedling growth. Therefore, it was felt desirable to study the effects on seed germination and seedling growth of opener types and crop residue conditions in a controlled wet soil under controlled climatic conditions.

3.2 EFFECTS OF DIRECT DRILLING OPENERS ON SEED/SEEDLING PERFORMANCE IN THE PRESENCE AND ABSENCE OF CROP RESIDUE, UNDER CONTROLLED CLIMATIC CONDITIONS

3.2.1 Introduction:

The performances of three direct drilling opener designs were tested, in terms of their ability to promote barley seedling emergence in wet soils, in the presence and absence of crop residue. The experimental technique utilised large (0.5 tonne) undisturbed turf blocks which were drilled in the field with a special rig and then removed to a glasshouse under a controlled temperature for 3 to 4 weeks. Two experiments (2 and 3) were conducted. Experiment 2 was conducted under simulated rain conditions, while Experiment 3 involved a rising temporary water table without rain.

Measurements included oxygen diffusion rates around the groove profiles, soil moisture content, soil bulk density, soil temperature, numbers of earthworms, seed germination, seedling emergence counts and root weights.

Specific Objectives:

The main objectives of these two experiments were:

To compare the performance of three opener types in their ability to form suitable habitats for seed germination and seedling emergence.

To assess the effects of surface crop residue on seed germination and seedling emergence.

To study the effects of the groove geometry and surface residue on oxygen diffusion rates (ODR) around the groove profiles.

To examine the effects of residue and openers on earthworm populations in the vicinity of the groove profiles.

3.2.2 Materials and methods:

(a) Tillage bin technique:

The use of soil bins is not new in scientific studies of soil-plant-machine relations. Scientists and engineers have used disturbed soil samples and/or artificially packed bins for some time to study soil physical behaviour, soil machine mechanics, and soil-plant interactions. (Scotter, 1976; Choudhary and Baker, 1977; Gupta, 1967). Variable ambient conditions have made it necessary to use such techniques mainly indoors, and even in controlled climatic conditions, in order to accurately formulate qualitative and quantitative interactions.

By definition, it is clearly necessary to use undisturbed soil samples, representative of field conditions, for direct drilling studies. The importance of using a tillage bin technique in direct drilling studies is supported by the fact that fundamental soil physical parameters and their interactions with opener designs and ambient conditions have not been well understood and interpreted using field studies (Baker, 1976).

Baker (loc cit) explained a mechanized technique for extracting "undisturbed" turf blocks from the field and outlined the merits of their use in laboratory tillage studies. This technique has been used by others, in order to accurately formulate qualitative and quantitative interactions (Mai, 1978; Choudhary, 1979; J. Mitchell, pers comm, 1983). In the present study, use was made of these soil bins (with a modified technique) to investigate the interactions of soil physical factors, ambient conditions and direct drilling techniques.

Open-ended steel-sided bins (measuring 1.8 m long, 660 mm wide and 200 mm deep) were pulled into turf-covered Tokomaru silt-loam soil, situated at Massey University, using a special cutter (Baker, 1976). These bins remained in the soil which were drilled with a special tractor-operated rig. Baker (loc cit), Mai (loc.cit) and Choudhary (loc.cit) had used a technique where the bins were drilled in the laboratory with a travelling gantry and tool testing apparatus. The pre-drilling of tillage bins in the field provided nearly normal conditions for each opener while working in the field, such as operating speed. It was considered that laboratory drilling of the tillage bins may not have provided true field speed conditions which may have had some effect on soil shattering. This was thought to be an important aspect of opener function in a wet soil. The method of extracting these soil blocks is shown and summarised in Figure 11 .

(b) Preparation of surface residue conditions:

Because of the time of the year, no recent crop stubble or trash was available in the experimental field. To create surface residue conditions a pasture was allowed to grow to about 200-mm in length. The pasture was sprayed with glyphosate, at a rate of 5.6 l/ha, mixed with dicamba at 1.5 l/ha, using a pedestrian knapsack boom sprayer, 21 days before the seed drilling operation. The tillage bins were pulled into the soil with its sprayed pasture, 7 days before drilling. At the same time the crop residue was cut and removed from half the bin surfaces (see experimental design) to create no-residue conditions.

(c) Experimental design:

The following treatments were considered important to attain the objectives of this study.

1. Three contrasting opener types (winged, triple disc and hoe).
2. Two levels of surface residue ("no-residue" and the residue remaining from the herbicide-killed pasture - "residue").
3. Methods of maintaining a soil of high moisture content (simulated rain conditions; and temporary high water table conditions).

Figure 11: Turf block extraction process.

(a). Initiation of turf cutter and bin travel into soil.
(b). Tillage bin at full depth.
(c). Tillage bin after drilling in situ.

Constraints:

A number of limitations were imposed on the experimental design because of the facilities available.

There were a maximum number of 12 bins available at any one time.

There was only one climatic room (glasshouse) available at any one time which could comfortably accomodate 9 tillage bins.

In each soil block a total of three grooves at 150-mm spacing were possible.

In order to minimise the possible influence of one groove or opener upon an adjacent groove, only one type of opener was used per bin.

Because of these restrictions it was not possible to compare all treatments in one large experiment under controlled conditions. This also limited the numbers of replicates to three. It was therefore decided to divide the experimental programme into two separate experiments. The comparisons to be made within each of these experiments involved the opener types and two contrasting surface residue conditions.

Experiment 2:

Tillage bins were drilled at random in the field at a moisture content in the mid zone of the "available" range, and then removed to the glasshouse where they were kept under a simulated rain condition, with an intensity of 5 mm per hour for 4 hours a day, for 21 days.

Experiment 3:

Tillage bins were drilled at random in the field at a moisture content in the mid zone of the "available" range, and then removed to the glasshouse where they were kept under conditions of a temporary high water table for 4 hours a day, for 21 days.

Bins were arranged in blocks of 3 in the glasshouse. In this way, each split-plot experiment consisted of 6 treatments with three replicates. For each experiment new bins were extracted. Each soil bin was divided into two residue levels by cutting and removing the residue from one half. The bin was then drilled with one opener type (main treatment). Soil blocks remained in the glasshouse until seedling emergence counts had stabilised, which was usually after 21 days. Figure 12 shows the split-plot design in the glasshouse for both experiments.

(d) Climatic conditions during experimental period:

It was thought appropriate to test the grooves of direct drilling openers in climatic conditions representative of a wet-warm regime. Data relating to wet-cool conditions were available from English studies (Ellis et al, 1975; Lynch, 1977, 1978; and Lynch et al, 1980), but little comparable information was available relating to wet-warm conditions. Thus, all bin experiments were conducted in a glasshouse in which the nominally controlled temperature range was maintained at 20-25 ^{o}C day and night. A sample of a daily record of day/night (for a week) temperature and relative humidity changes inside the glasshouse within a nominally controlled temperature range is shown in Appendix 3a.

These climatic conditions prevailed from the day the drilled soil blocks were brought into the glasshouse, until a seedling emergence plateau had been reached.

For simulated rainfall onto the undisturbed soil blocks in these tillage bins, a soak-hose was suspended above the bins, and 20-mm of "rain" applied per day, with an intensity of 5 mm per hour. The soak-hose technique had been used by Mai (1978). This technique was considered to be economical, simple and efficient in creating a simulated rain condition of the desired intensity, although no control over droplet size was attempted. Indeed the droplets appeared to be somewhat finer than might be expected from natural rainfall of this intensity.

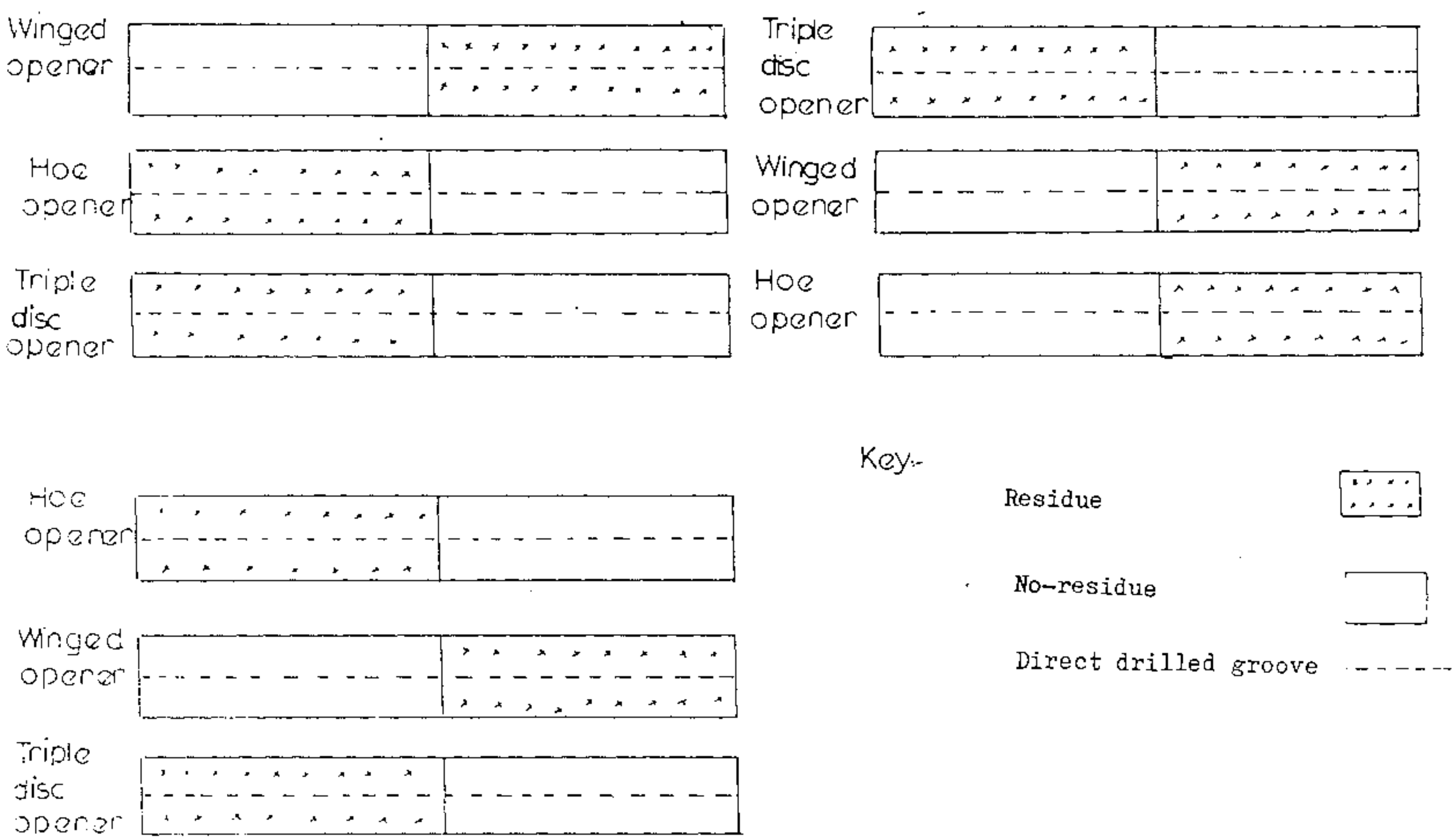


Figure 12: Experimental lay-out of tillage bin experiments (2 and 3) conducted in a glass-house.

To study the effects of a temporary high water table on seed germination and seedling performance after direct drilling, a high water table condition was created by placing the tillage bins in steel trays and adding water to within 150 mm of the surface of the soil. The bottoms of the bins were perforated for this purpose and were raised 50-mm above the surface of the trays. The temporary high water table condition remained for 4 hours a day, after which the bins were drained.

Water in simulated rain or high water table conditions was not applied to all replicates simultaneously. Rather each replicate was wetted in a sequence of ODR and other measurements in such a way that there was a consistent time interval between wetting and measuring with each replicate. This was considered important as drainage intervals were then constant (20 hours) which were thought to influence ODR in particular.

3.2.3 Measurements:

(a) Oxygen diffusion rate (ODR) around the groove profiles:

Four platinum micro-electrodes were available to take ODR measurements around the groove profiles at any one time.

1. Measurements were made around the groove at sixteen points in a square grid pattern (Figure 13) where each point was separated by 30 mm. The first set of measurements at one depth was made with four points (row (a) in Fig. 13). After five minutes the micro-ampere current readings were recorded and all four electrodes were then relocated at deeper positions to form the second four-point row (row (b) Fig. 13). The same procedure was repeated for taking measurements at 30 mm incremental depths (rows (c) and (d) in Fig. 13).
2 As the capacity of the equipment was limited, in order to save time in recording all 16 measurements, the ODR measurements were restricted to one randomly selected side of

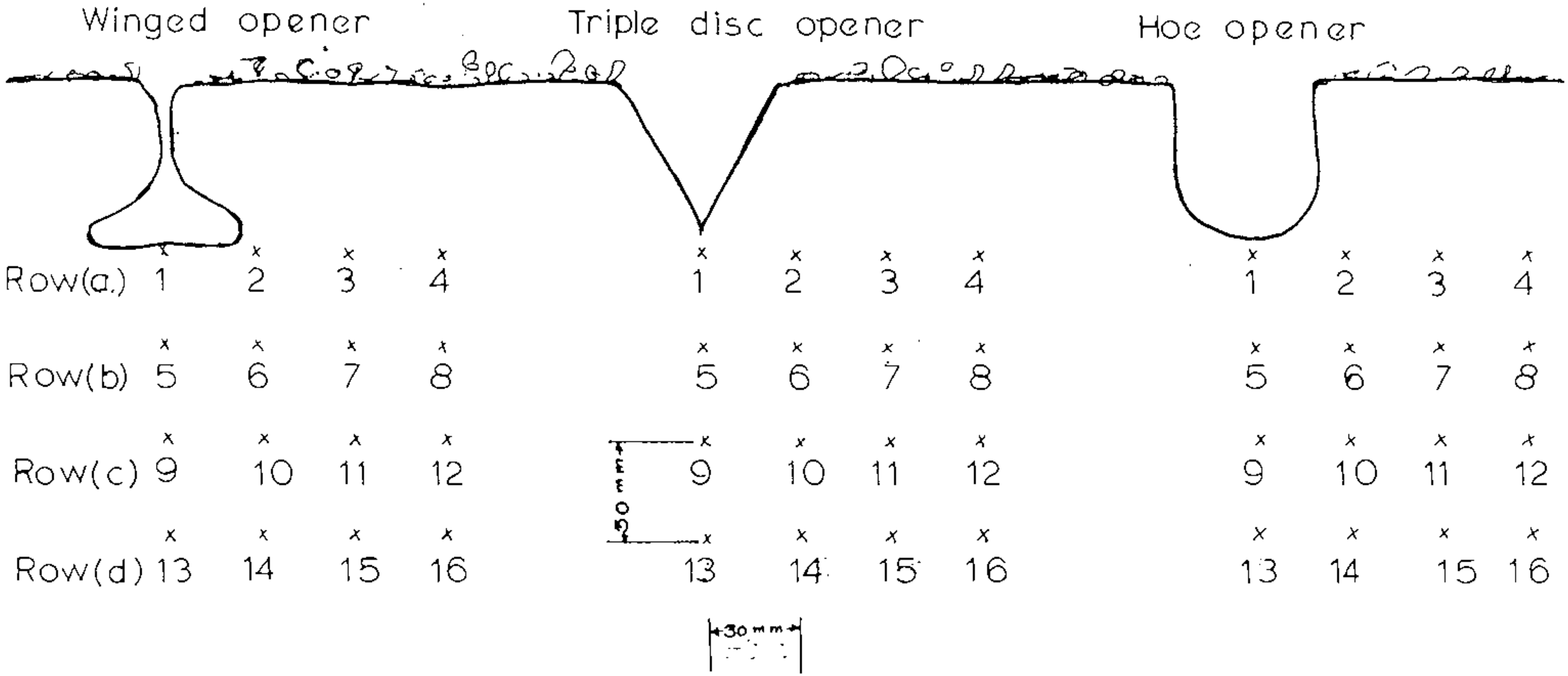


Figure 13: A grid pattern for measuring oxygen diffusion rate(ODR), soil bulk density and soil moisture content around direct drilled grooves (experiments 2 and 3).

the symmetrical grooves. The other side of the groove was used for soil bulk density and soil moisture measurements. Nevertheless, with all grooves a periodic check was made to compare ODR measurements from each side of sample grooves, and no differences were found between sides. This confirmed the symmetry of the grooves created by the direct drilling openers.

3. In this way a total of 16 measurements were made on one side of the groove profile including a point at the centre of the groove. This took approximately 20 minutes per replicate.

4 The measurements, recorded in micro-amperes were converted into oxygen diffusion rate (ODR) in $gx10^{-8}/cm^{2}/min$ using the conversion given in Section 3.1.3.

(b) Measurement of seed fate and root weight:

The measurements of seed/seedling performances and root weights were made after day 21, adopting the techniques described earlier in Section 3.1.

(c) Soil bulk density and soil moisture measurements:

In these experiments a similar soil sampler to that used in field experiment and described in Section 3.1, was used. The soil samples collected for soil bulk density measurements, were also used for soil moisture measurements, as a further means of indirectly representing the soil aeration status.

The samples were taken on an identical grid pattern of sixteen points, as was used for ODR measurements. Usually soil bulk density/moisture content sites were located in the opposite side of the groove to the ODR side.

Figure 14: Core sampler (120 mm dia x 100 mm length) used for estimating earthworm populations around a direct drilled groove.

(d) Soil temperature:

Soil temperature measurements were felt to be important to help explain the effects of the contrasting opener types on the soil micro-environment. A number of thermocouples were constructed, using copper-constantan and were moisture-sealed in epoxy resin. These were buried within the direct drilled grooves at seed level after drilling. Daily in-groove soil temperature measurements were recorded in the same sequence, using a micro-voltmeter with an in-built reference junction. Soil temperature was measured until seedling emergence counts had stabilized. Choudhary (1979) and Baker (1976) had used a similar technique to measure in-groove soil temperatures when direct drilling under dry soil conditions. A thermocouple calibration curve is shown in Appendix 3b.

(e) Estimation of earthworm populations:

To estimate earthworm populations, a choice of methods existed. These included hand sorting, soil washing, electric current, chemicals, and heat extraction. Several workers have compared the relative efficiency of extracting earthworms from the soil by these methods (Svendson, 1955; Raw, 1959; Edwards and Lofty, 1972; J. Springett, pers. comm, 1983). These workers felt that each method was suitable for specific requirements, but all agreed that a hand sorting technique was the most reliable and efficient. Mai (1978) used a hand sorting technique to estimate earthworm populations around direct drilled groove profiles.

In the present study, soil samples were collected from around the groove profiles by collecting a vertical core of 120 mm diameter and 100 mm effective length (Figure 14). Earthworms were hand sorted and the numbers recorded. The earthworms dissected (half) by core sampler were also counted.

3.2.4 Experiment 2

Seedling emergence under simulated rain conditions

(a) Introduction:

The principal objective of this experiment was to study the effects of three opener types on seedling emergence under simulated rain conditions, in the presence and absence of crop residue. Care was taken that the simulated rainfall of 20 mm a day (with an intensity of 5 mm per hour) was identical for each plot and replicate. The glasshouse temperature was maintained at 20-25 ^{o}C day and night. Oxygen diffusion rate measurements in the profile around the direct drilled grooves were taken on days 0, 5, 10, 15 and 20, using platinum micro-electrodes at a potential of -0.65 volts. Temperature variations in the vicinity of the seed grooves were measured using thermocouples. A hand sorting technique was used to count earthworm populations around the groove profiles at the end of the experiment. Barley seed (variety Magnum, of 94% laboratory germination) was sown.

(b) Results and discussion:

Seedling emergence:

Table 5 shows the effects of opener types on seedling emergence and seed fate of direct drilled barley in the presence and absence of crop residue, together with the interactions between these two parameters. Analyses of variance of main plots showed that all differences in seedling emergence percentages, attributable to opener types, were significant ($P<0.05$). The grooves of the winged opener recorded the highest seedling emergence count of 58.6%, followed by the grooves of the hoe opener (48.3%). The percentage count for the grooves of the triple disc opener was only 25.7%.

The contrasting crop residue conditions had a highly significant effect ($P<0.01$) on seedling emergence percentages. The percentage

Table 5: Effects of opener types and contrasting crop residue conditions, on the fate of direct drilled barley seeds, under simulated rain conditions.

Seed fate	Openers			Residue		Interactions				
	Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
Seedling emergence (%)	58.6	25.7	48.3	34.3	54.1	NR	43.8	26.2	32.9	SED1=3.15
	Aa	Bc	Ab	Bb	Aa	R	73.3	25.2	63.8	SED2=1.07
Ungerminated or dead seeds (%)	11.5	53.1	23.5	30.3	28.4	NR	15.5	46.3	29.1	SED1=2.94
	Cc	Aa	Bb	Aa	Aa	R	7.5	59.8	17.9	SED2=2.78
Germinated but unemerged seedlings (%)	29.7	21.2	27.7	35.4	16.9	NR	40.7	27.5	38.0	SED1=2.65
	Aa	Ab	Aa	Aa	Bb	R	18.7	14.9	17.3	SED2=2.72
Dry matter weights of roots (mg)	17.2	9.3	15.2	10.4	17.3	NR	10.3	9.6	11.3	SED1=10.3
	Aa	Bb	Aa	Bb	Aa	R	24.0	9.0	19.0	SED2=3.0

*NR = No surface residue present
**R = Surface residue present
Unlike letters in a row denote Significant differences (upper case, P<0.01; lower case, P<0.05)
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

seedling emergence across all opener types was 34.3% under no-residue conditions compared with 54.1% under surface residue conditions.

There were strong interactions between opener types and crop residue conditions, with residue appearing to be more influential than opener types, at least with the winged and hoe openers. For example, the grooves of the winged opener under residue showed the highest emergence, followed by the grooves of the hoe opener in residue. The grooves of the hoe and winged openers without residue, appeared to be superior to those of the triple disc opener with and without residue. The apparent insensitivity of the triple disc opener to residue may be explained by the seed fate data discussed below.

Fig. 15 shows the rate of seedling emergence for the three opener types under the two crop residue conditions. It appears that all treatments plateaued at about the same time (day 15), although those which eventually experienced the highest maximum emergence counts also showed the most rapid rates of emergence, especially during the first 5 days.

Ungerminated/dead seeds:

Table 5 also shows the effects of opener types and contrasting crop residue conditions on ungerminated/dead seeds, and the interactions between these two parameters. Table 5 shows that there was a significantly ($P<0.01$) larger number of ungerminated or dead seeds in the triple disc opener grooves (53.1%) compared with those of the hoe opener (23.5%), which itself had a significantly larger count than the grooves Of the winged opener (11.5%).

The contrasting surface residue conditions had no significant effects on the number of ungerminated seeds. However, the interactions between opener types and surface residue conditions clearly favoured the winged opener operating in residue. On the other hand, the triple disc opener in residue resulted in the highest count of dead or ungerminated seeds. As this was the only opener which was seen to push residue down into the groove in-contact with the seeds, perhaps this had had an adverse effect on germination as suggested by Ellis <u>et al</u> (1975); Lynch (1977,1978); and Lynch <u>et al</u> (1980).

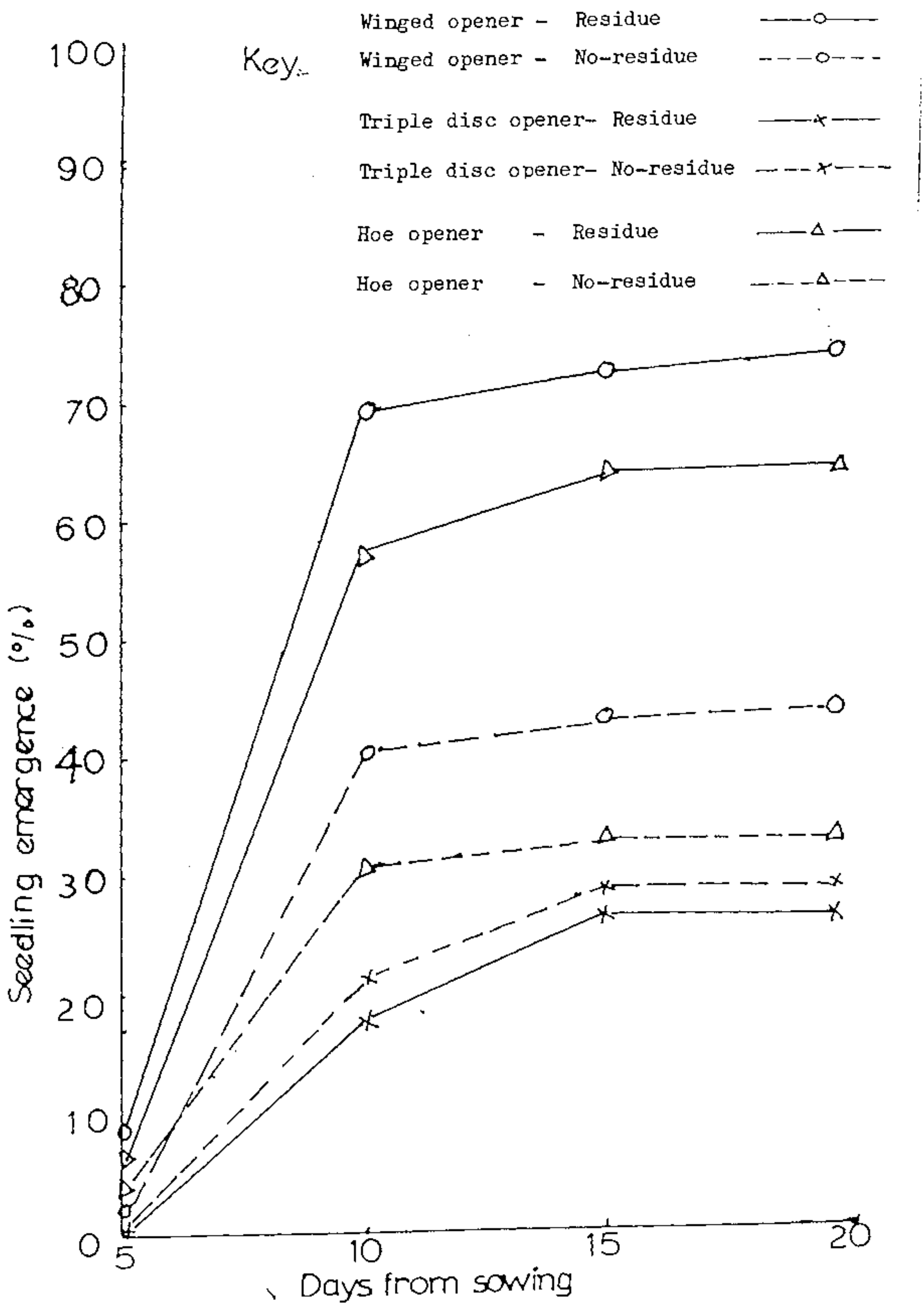


Figure 15: Effects of direct drilling opener types and contrasting crop residue conditions on seedling emergence rates of barley, under simulated rain conditions.

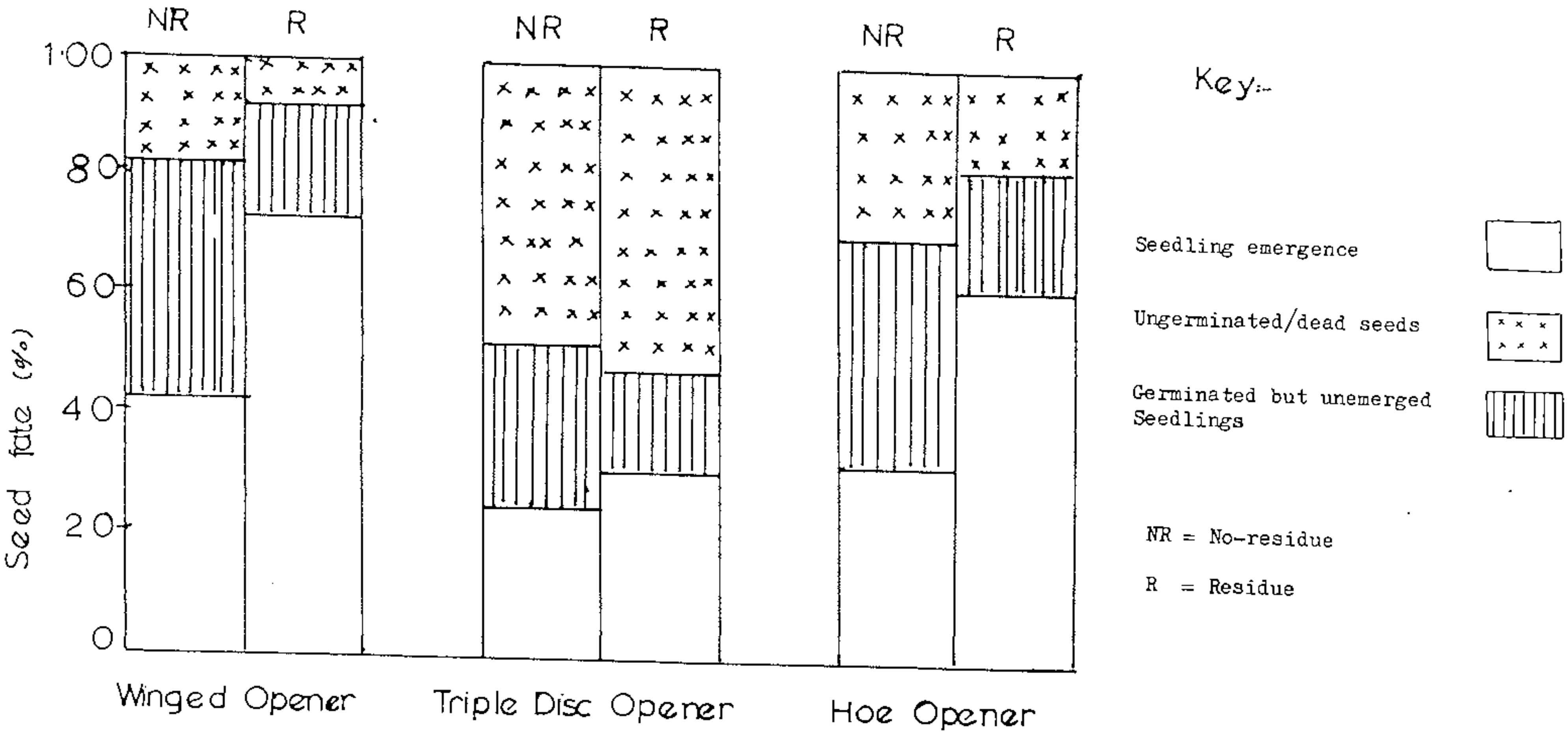


Figure 16: Effects of opener types and contrasting crop residue conditions on **cumulative** seed fate of barley under simulated rain conditions.

"Germinated but unemerged" seedlings

Table 5 also lists the effects of opener types and contrasting crop residue conditions on "germinated but unemerged" seedlings, and the interactions between these two parameters. From the Table there appeared to be only a comparatively small difference in counts of "germinated but unemerged" seedlings although there were significantly ($P<0.05$) larger numbers of such seedlings in both the winged (29.7%) and hoe (27.7%) opener grooves than in the grooves of the triple disc opener (21.2%).

The contrasting crop residue conditions appeared to have had a highly significant ($P<0.01$) effect on the numbers of "germinated but unemerged" seedlings. Counts of such seedlings in no-residue conditions (35.4%) were more than twice those in the residue conditions (16.9%).

The interactions between opener types and surface residue conditions showed that all openers were consistent in responding favourably to residue. This might suggest, at least in the grooves of the triple disc, that seed/residue contact had had more effect in retarding seed germination, than in retarding growth of those seedlings which had germinated.

Summary of seed fate:

The collective seed fate data are shown in Figure 16. From the Figure it is apparent that with the triple disc opener the major problem was dead or ungerminated seeds, whereas the largest category of seeds not counted as emerged in the winged and hoe opener grooves were "germinated but unemerged".

The Figure also shows that under these soil and climate conditions a reasonable level of barley seedling emergence could be gained through residue by using either the winged (58.6%) or hoe (48.3%) openers.

Dry matter weight of roots:

Table 5 also shows the effects of opener types and crop residue conditions on dry matter weights of roots per plant, and the interactions between these two parameters. From the Table, root weights per plant were significantly ($P<0.01$) lower in the triple disc opener grooves (9.3 mg) compared with both the winged (17.2 mg) and hoe (15.2 mg) opener grooves, which were not significantly different.

The contrasting crop residue conditions had a highly significant ($P<0.01$) effect on root weights per plant. The mean root weight per plant across all opener types under residue conditions (17.3 mg) was 66% higher than the mean root weight per plant under no-residue conditions (10.4 mg).

The interactions between opener types and surface residue conditions indicated that both the winged and hoe openers under residue conditions performed better than the triple disc with or without residue.

Oxygen diffusion rate (ODR)
around the groove profiles:

Table 6 lists the effects of opener types and contrasting surface residue conditions on ODR, and the interactions between these two parameters on days 0, 5, 10, 15 and 20. From the Table it is apparent that on days 0 and 5 the mean ODR values of all sixteen monitoring points were not significantly different in the profiles around the grooves of the winged, triple disc and hoe openers. On day 10, the grooves created by the triple disc showed a slightly, but significantly ($P<0.01$), lower ODR regime (15.6×10^{-8} g/cm^2/min) compared with the regimes around the grooves of the winged (16.0×10^{-8} g/cm^2/min) and hoe (17.0×10^{-8} g/cm^2/min) openers, which were not significantly different. The same trend continued until day 15. However, on day 20, although the ODR regime near the groove profile of the triple disc opener was still significantly ($P<0.01$) the lowest of all three openers, the grooves of the hoe opener had by then attained a significantly ($P<0.01$) higher regime than those of the winged opener.

The contrasting residue conditions appeared to have no significant effect on the ODR regimes on days 0 and 5. But on days 10, 15 and 20, the mean ODR of all opener types under crop residue conditions was significantly ($P<0.01$) higher than under no-residue conditions.

Table 6: Effects of direct drilling opener types and contrasting crop residue conditions, on oxygen diffusion rate (ODR), under simulated rain conditions.

Days from sowing	Openers			Residue		Interactions				
	Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
		ODR $(g \times 10^{-8}/cm^2/min)$								
0	47.2	46.9	48.8	47.9	47.3	NR	46.5	47.6	49.5	SED1=0.81
	Aa	Aa	Aa	Aa	Aa	R	47.2	46.2	48.0	SED2=0.83
5	17.4	18.3	16.2	17.1	17.5	NR	16.8	19.1	15.3	SED1=1.01
	Aa	Aa	Aa	Aa	Aa	R	18.0	17.4	17.2	SED2=0.94
10	16.0	15.6	17.0	14.7	17.8	NR	14.7	14.5	14.8	SED1=0.27
	Ab	Bb	Aa	Bb	Aa	R	17.4	16.8	19.1	SED2=0.23
15	13.5	11.8	13.0	11.0	14.5	NR	11.8	10.2	11.1	SED1=0.43
	Aa	Ab	Aa	Bb	Aa	R	15.1	13.4	14.9	SED2=0.29
20	13.9	13.0	14.9	11.6	16.3	NR	12.1	10.3	12.3	SED1=0.44
	Bb	Cc	Aa	Bb	Aa	R	15.8	15.7	17.4	SED2=0.57

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case $P<0.05$).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

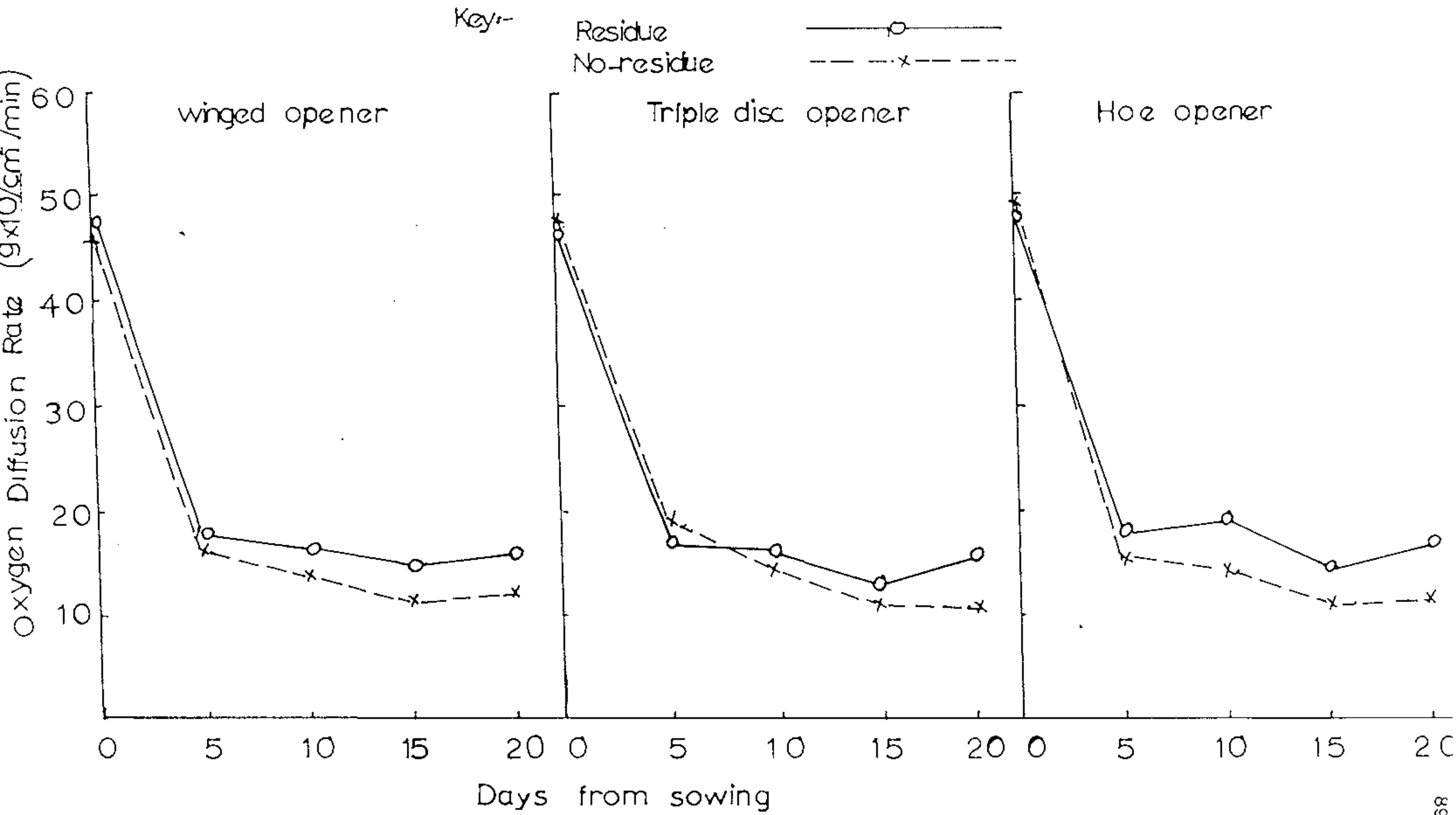


Figure 17: Effects of direct drilling opener types and contrasting crop residue conditions on changes in oxygen diffusion rate with time, under simulated rain conditions.

The interactions between opener types and crop residue conditions did not appear to show any consistent trends between days 0-5. But between days 10-20, each of the openers showed consistently higher ODR regimes in residue than no-residue conditions.

Figure 17 shows the changes in ODR regime for each opener type with time under the contrasting crop residue conditions. It appears from all curves that between days 0 and 5 there were rapid reductions in mean ODR values under both contrasting residue conditions, regardless of the geometry of the grooves. However, between days 5 and 15, ODR regimes remained almost constant under residue conditions, but continued to fall slightly in the absence of surface residue. The curves also illustrate that as the experiment advanced, ODR appeared to be consistently greater under crop residue conditions than under no-residue conditions.

Figures 18 (a-c) are a family of iso-ODR lines which illustrate the average cumulative ODR regimes (days 5-20) for each groove and residue condition. The data represent measurements from one side of the grooves but are shown for both sides because of the symmetry of the grooves (see Section 3.2.2). The Figures are arbitrarily divided into three zones, which are based on the published tolerance data for barley (Letey et al, 1962b; see review of literature). The low ODR zone represents ODR values of 15×10^{-8} g/cm^2/min and below. The medium zone is between 15-18×10^{-8} g/cm^2/min, and the high zone represents ODR values of 18×10^{-8} g/cm^2/min and above. The Figures show that under crop residue conditions the medium ODR range extended down to 60-75 mm below the base of the grooves of the winged (Fig. 18a above) and hoe (Fig. 18c above) openers. By contrast, under no-residue conditions the depth of this medium ODR zone was much shallower (30-45 mm) in these grooves (Figures 18a and 18c below). Both these openers showed large zones of high ODR immediately beneath the groove bases under residue conditions. The width of the medium ODR zones with the winged and hoe openers, under both residue and no-residue conditions, extended upto 90 mm either side of the groove centre (which was the limit of measurement).

With the grooves of the triple disc opener, the medium ODR zone extended down to 75 mm and 45 mm in the residue (Fig. 18b above) and no-residue (Fig. 18b below) conditions respectively. However, the width of this zone was very restricted, being about 25 mm either side of the

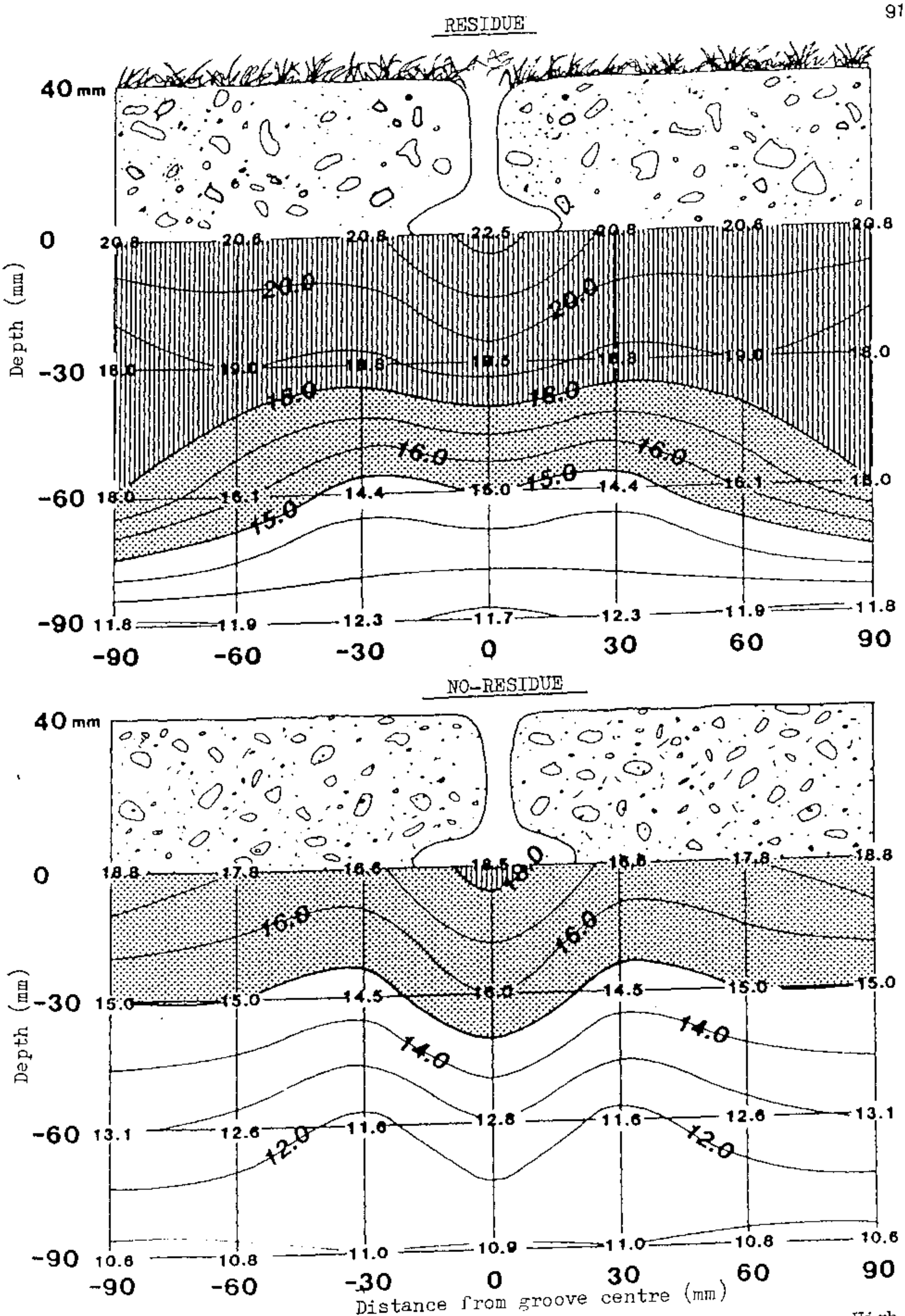


Figure 18a: Average **cumulative** oxygen diffusion rate zones, created around a direct drilled groove (Winged opener, days 5-20), under simulated rain conditions.

High

Medium

Low

$(g \times 10^{-8}/cm^2/min)$

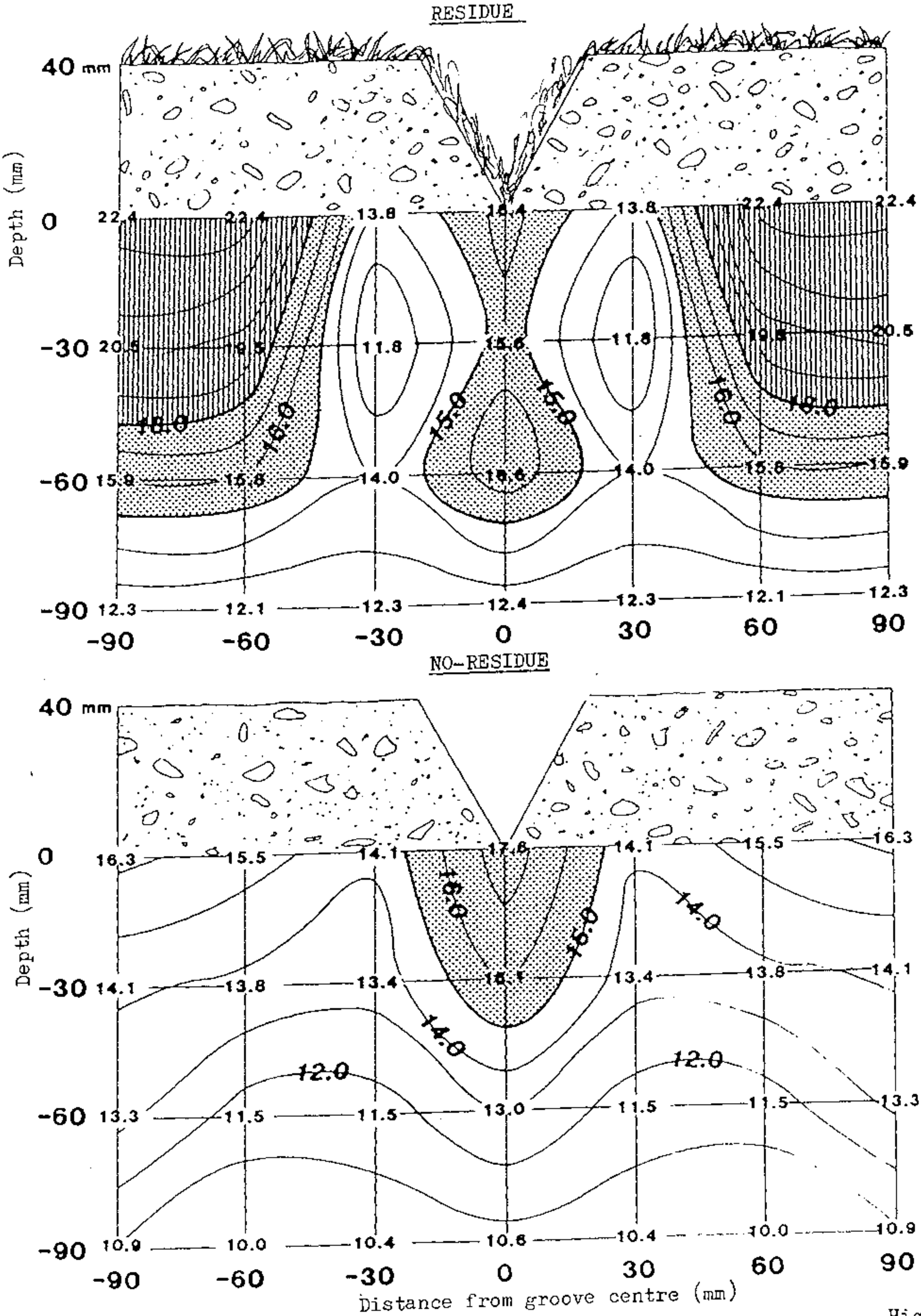


Figure 18b: Average cumulative oxygen diffusion rate zones, created around a direct drilled groove (Triple disc opener, days 5-20), under simulated rain conditions.

$(g \times 10^{-8} cm^{-2} min)$

High
Medium
Low

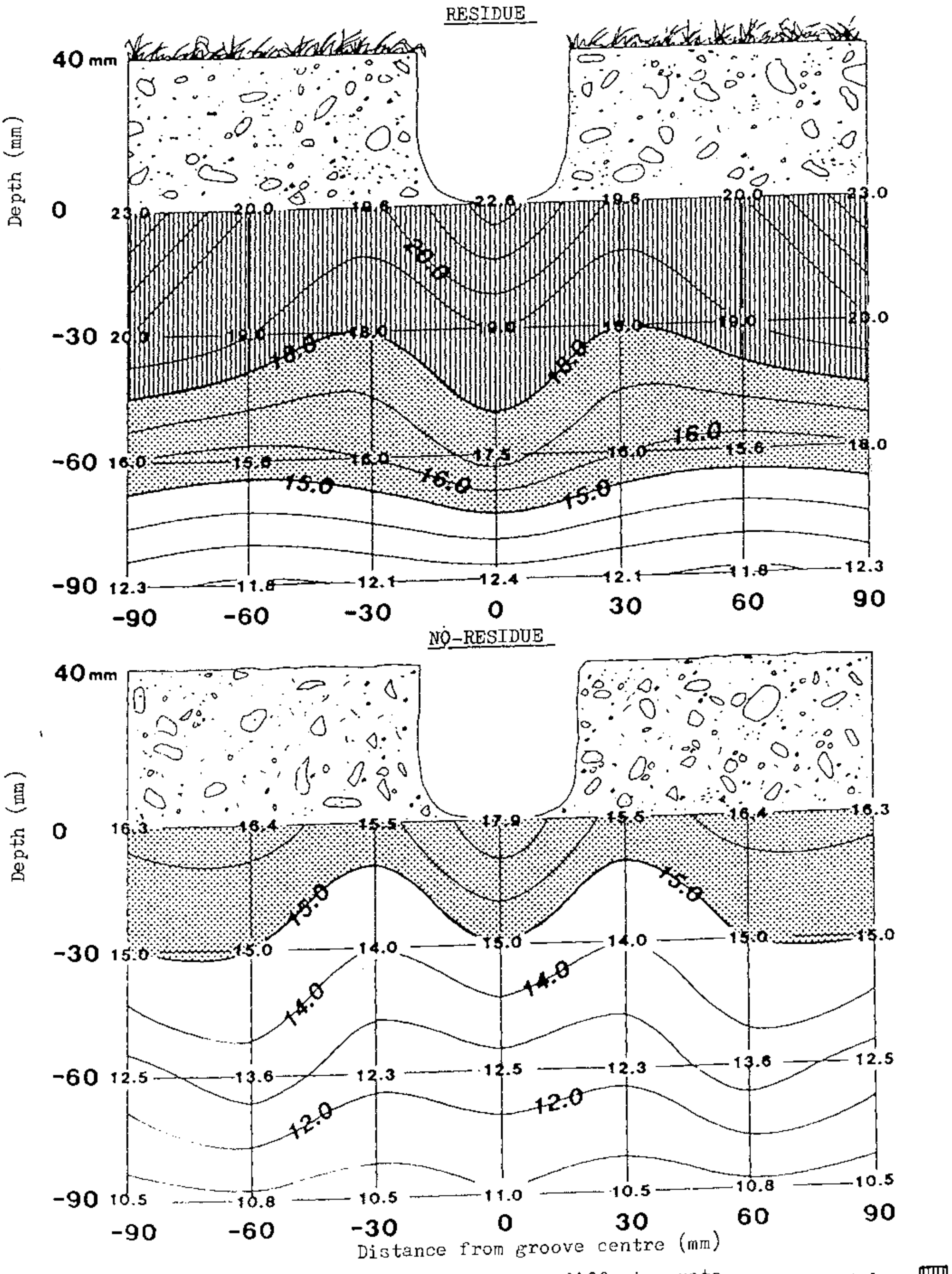


Figure 18c: Average cumulative oxygen diffusion rate zones, created around a direct drilled groove (Hoe opener, days 5-20), under simulated rain conditions.

($gx10^{-8}/cm^2/min$)

groove with no-residue, and only 15 mm under residue conditions. The occurrence of a secondary medium ODR zone with the triple disc, was thought to be of no consequence as a 20 mm zone of low ODR separated the two medium ODR zones. The grooves created by the triple disc opener showed no zone of high ODR except one which was also isolated from the groove by a 20 mm zone of low ODR.

Earthworm populations:

Table 7 shows the effect of opener types and contrasting surface residue conditions on earthworm populations around the groove profiles, and interactions between these two parameters. From the Table, it appears that a significantly ($P<0.01$) larger number of earthworms occurred around the groove profiles of the winged (20.3) and hoe (19.0) openers, compared with that of triple disc (7.3) opener. In this respect there was no significant difference between the winged and hoe openers.

The contrasting crop residue conditions also appeared to have a significant effect on earthworm populations around the groove profiles. Under residue conditions, the numbers of earthworms were significantly ($P<0.01$) larger (20.7) than under no-residue conditions (10.4).

The interactions between opener types and contrasting crop residue conditions suggested that even under residue conditions earthworms were less attracted to the grooves of the triple disc opener than to the grooves of the winged (and perhaps also the hoe) openers without residue. As expected, the grooves of the latter two openers attracted the greatest number of earthworms in all treatments, when residue was present.

In-groove soil temperature:

Table 8 shows the effects of opener types and contrasting surface residue conditions, on mean in-groove soil temperatures across all sampling dates, and the interactions between these two parameters. From the Table there appeared to be no significant ($P<0.05$) effects on in-groove temperature which were attributable to opener types. These findings were similar to those obtained under dry soil conditions by Baker (1976) and Choudhary (1979).

Table 7: Effects of direct drilling opener types and contrasting crop residue conditions, on earthworm populations around the groove profiles, under simulated rain conditions.

Openers			Residue		Interactions				
Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
Populations (numbers per core ***)									
20.3	7.3	19.0	10.4	20.7	NR	13.3	6.7	11.3	SED1=2.49
Aa	Bb	Aa	Bb	Aa	R	27.3	8.0	26.7	SED2=1.79

Table 8: Effects of direct drilling opener types and contrasting crop residue conditions, on in-groove soil temperature, under simulated rain conditions.

Openers			Residue		Interactions				
Winged	Triple disc	Hoe	NR*	R**	Openers Residue	Winged	Triple disc	Hoe	
In-groove soil temperature (^{o}C)									
22.1	22.2	22.4	21.8	22.6	NR	21.6	21.9	22.1	SED1=0.195
Aa	Aa	Aa	Bb	Aa	R	22.5	22.5	22.7	SED2=0.124

*NR = No surface residue present.
**R = Surface residue present.
***Core = 1.13 litres volume

Unlike letters in a row denote significant differences (upper case, P<0.01; lower case P<0.05).
SED1=Standard error of differences within opener types.
SED2=Standard error of all other interactive differences.

On the other hand, the contrasting surface residue conditions had a small (0.8^{o} C), but highly significant (P<0.01) effect on the mean in-groove soil temperature of all opener types.

The residue conditions caused a rise in the mean in-groove soil temperatures which the interactions showed to be consistent for each of the opener types. This rise might at first have appeared inconsistent with other published data for untilled seedbeds (Lal, 1976; Lal, 1978; Larson, 1970), but it must be appreciated that the data above related only to the groove area (which usually had some or all of the residue removed from immediately over the seed zone - the winged opener being the exception), and that soils were very wet. Perhaps micro-organism respiratory activity was also greater under the wet residue, leading to a small temperature rise.

Soil bulk density around
the groove profiles:

Soil bulk density measurements were taken around the groove profiles on days 0, 5, 10, 15 and 20. Soil samples were collected from sixteen points on a similar grid to those selected for ODR measurements.

Table 9 shows the effects of opener types and contrasting surface residue conditions on soil bulk density around the groove profiles, and the interactions between these two parameters. From the Table, there appeared to be no significant (P<0.05) differences in soil bulk densities, as a function of opener types on day 5. However, on days 0, 10 and 15 the soil around the grooves of the triple disc opener showed a significantly (P<0.01) higher bulk densities than the soil around the hoe opener grooves which was itself significantly more dense than that around the winged opener grooves. Mai (1978) had earlier noted high bulk densities at the base and sides of the grooves of the triple disc opener, compared with the grooves created by the winged opener. On day 20 the bulk density around the grooves of the hoe opener (1.17 g/cm^{3}) was significantly (P<0.05) lower than that of the winged opener (1.19 g/cm^{3}), which has itself less than the triple disc opener (1.21 g/cm^{3}). It is difficult to see any logical reason for the reversal of the ranking of the winged and hoe openers on day 20, since at all other previous readings earthworm activity had not been different between these two

Table 9: Effects of direct drilling opener types and contrasting crop residue conditions, on soil bulk density around the groove profiles, under simulated rain conditions.

Days from sowing	Openers			Residue		Interactions				
	Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
	Bulk density (g/cm^3)									
0	1.02	1.09	1.06	1.06	1.04	NR	1.05	1.09	1.05	SED1=0.012
	Bc	Aa	Ab	Aa	Bb	R	0.98	1.08	1.06	SED2=0.010
5	1.11	1.14	1.13	1.13	1.13	NR	1.12	1.14	1.13	SED1=0.016
	Aa	Aa	Aa	Aa	Aa	R	1.11	1.15	1.12	SED2=0.017
10	1.14	1.19	1.15	1.18	1.15	NR	1.17	1.20	1.18	SED1=0.004
	Bc	Aa	Bb	Aa	Bb	R	1.13	1.18	1.13	SED2=0.005
15	1.15	1.22	1.19	1.21	1.17	NR	1.19	1.24	1.21	SED1=0.004
	Bc	Aa	Bb	Aa	Bb	R	1.12	1.19	1.18	SED2=0.005
20	1.19	1.21	1.17	1.23	1.16	NR	1.22	1.24	1.21	SED1=0.006
	Ab	Aa	Bc	Aa	Bb	R	1.17	1.18	1.14	SED2=0.007

*NR = Surface residue present.
**R = No surface residue present.
Unlike letters in a row denote significant differences (upper case, P<0.01; lower case P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

openers.

As with the opener - bulk density readings, the contrasting crop residue conditions appeared to have no significant effects on soil bulk densities on day 5. However, on days 0, 10, 15 and 20 the mean bulk density across all opener types under crop residue conditions was significantly ($P<0.01$) lower than under no-residue conditions.

The interactions between opener types and surface residue conditions appeared to confirm that the trends of the main and sub-treatment effects, applied to each opener and residue condition.

Soil moisture content around
the groove profiles:

The experiment was initiated at average soil moisture contents (at a 40 mm depth) of approximately 23.0% (d.b.) and 25.0% (d.b.) for the no-residue and surface residue conditions respectively. Soil moisture contents were taken after drilling from around the groove profiles at the same 16 points as for soil bulk density measurements, and were recorded on days 0, 5, 10, 15 and 20.

Table 10 shows the effects of opener types and contrasting surface residue conditions, on soil moisture contents around the groove profiles, and the interactions between these two treatment factors. It appears from the Table, that on day 0 the grooves of the triple disc and hoe openers had significantly ($P<0.05$) lower soil moisture contents than the grooves of the winged opener.

On days 5 and 15 there were no significant differences amongst opener types, but on days 10 and 20 the moisture content of the grooves of the hoe opener was the lowest, while the grooves of the triple disc and winged openers remained not significantly different from each other. Perhaps this reflected the more open (drying) nature of the hoe opener grooves compared with the closed (winged) or narrower (triple disc) grooves.

The contrasting surface residue conditions had a significant ($P<0.05$) effect on soil moisture contents around the groove profiles on

Table 10: Effects of direct drilling opener types and contrasting crop residue conditions, on soil moisture content around the groove profiles, under simulated rain conditions.

Days from sowing	Openers			Residue		Interactions				
	Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
	Soil moistue content (% d.b)									
0	25.3	24.9	24.8	24.5	25.3	NR	25.0	24.2	24.1	SED1=0.18
	Aa	Bb	Bb	Bb	Aa	R	25.7	25.6	25.4	SED2=0.23
5	32.1	32.8	32.4	32.0	32.9	NR	32.1	32.3	31.7	SED1=0.89
	Aa	Aa	Aa	Aa	Aa	R	32.2	33.3	33.1	SED2=0.63
10	33.9	33.6	33.3	33.9	33.3	NR	33.8	33.8	34.0	SED1=0.19
	Aa	Aa	Ab	Aa	Bb	R	33.9	33.5	33.6	SED2=0.22
15	34.8	35.8	35.3	35.8	34.9	NR	35.3	36.2	33.7	SED1=0.40
	Aa	Aa	Aa	Aa	Bb	R	34.3	35.3	34.9	SED2=0.29
20	35.1	35.4	34.5	35.9	34.1	NR	35.9	35.9	35.9	SED1=0.34
	Aa	Aa	Bb	Aa	Bb	R	34.3	34.9	33.0	SED2=0.43

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote significant differences (upper case, P<0.01; lower case, P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

all days except day 5. On day 0 the crop residue conditions showed higher soil moisture contents (25.3% d.b) compared with the no-residue conditions (24.5% d.b). On days 10, 15 and 20, soil moisture contents under no-residue conditions were slightly but significantly higher than those under surface residue conditions.

The interactions showed no consistent trends and there appeared to be only minor differences amongst subtreatments.

3.2.5 Experiment 3

Seedling emergence under temporary high water table conditions:

(a) Introduction:

Experiment 2, under simulated rain conditions had shown low ODR and high soil bulk density regimes around a range of groove profiles under no-residue conditions. This situation was improved with two openers where surface residue remained in place, while with one other opener the situation remained unchanged, or deteriorated further. It was considered possible that these effects might have been influenced by the effects of impacting "rain" drops especially in the more open grooves. The main objectives of Experiment 3, therefore, were to study the performance of the three opener types used in Eexperiment 2 under a rising, but temporary high water table within the tillage bins. The high water table was maintained for 4 hours a day and then allowed to drain for 20 hours by using the technique explained in the Materials and Methods Section (3.2.2). In all other respects and measurements Experiment 3 was identical to Experiment 2.

(b) Results and discussion:

Seedling emergence:

Table 11 shows the effects of opener types on seedling emergence and seed fate of direct drilled barley in the presence and absence of crop residue, and the interactions between these two parameters. From the Table, it appears that the grooves of the winged and hoe openers were not significantly different, and recorded the highest seedling emergence (mean 50.5%) of the three openers tested. The percentage count for the grooves of the triple disc opener (42.1%) was the lowest of the three opener types, but was not significantly ($P<0.05$) different from the hoe opener.

The contrasting crop residue conditions had a highly significant

Table 11: Effects of direct drilling opener types and contrasting crop residue conditions, on the fate of direct drilled barley seeds, under temporary high water table conditions.

Seed fate	Openers			Residue		Interactions				
	Winged	Triple disc	Hoe	NR *	R **	Openers/ Residue	Winged	Triple disc	Hoe	
Seedling emergence (%)	54.8	42.1	46.2	41.6	53.8	NR	35.7	57.1	31.9	SED1=5.12
	Aa	Ab	Aab	Bb	Aa	R	73.8	27.1	60.5	SED2=5.52
Ungerminated or dead seeds (%)	17.8	32.9	21.6	25.2	23.0	NR	28.5	20.8	32.4	SED1=5.09
	Bb	Aa	Bb	Aa	Aa	R	7.2	51.0	10.9	SED2=6.65
Germinated but unemerged seedlings (%)	27.3	24.8	32.4	30.3	23.3	NR	35.8	21.9	35.7	SED1=5.56
	Aa	Aa	Aa	Aa	Ab	R	18.9	21.8	29.2	SED2=3.79
Dry matter weight of roots (mg)	23.1	17.8	22.0	19.6	23.3	NR	26.0	14.0	19.0	SED1=1.3
	Aa	Bb	Aa	Bb	Aa	R	21.6	20.3	25.0	SED2=1.2

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote Significant differences (upper case, P<0.01; lower case, P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

(P<0.01) effect on seedling emergence percentage. The counts across all opener types was 53.8% under residue conditions compared with 41.6% under no-residue conditions.

There were strong interactions between opener types and crop residue conditions, with residue appearing to be a more influential factor than opener types. For example, the winged opener, under residue, showed the highest emergence count followed by the hoe opener under residue. As in Experiment 2, the triple disc opener performed better under no-residue than under residue conditions, (although in this experiment the difference was much greater). In fact the grooves of the triple disc opener apeared to be superior to both the winged and hoe openers under no-residue conditions. It is difficult to see a reason for this latter effect. It might be suggested that the improved performance of the triple disc opener under no-residue conditions could have been because of the absence of "rain" drop impact in the more open grooves without the protection of the residue. On the other hand in no-residue, although the grooves of the hoe opener, (which were also open) performed better in this experiment in relation to the winged opener, their absolute emergence counts differed little between the two experiments. It was more a factor of the winged opener grooves performing less well, than the hoe opener grooves improving under the high water table conditions. The role of rain drop impact with the winged opener would appear to be obscure.

Figure 19 shows the rate of seedling emergence as affected by opener types under the two crop residue conditions. As with Experiment 2, it appears that all treatments plateaued at about the same time (day 15), and that those which experienced the highest maximum emergence counts, also showed the most rapid rates of seedling emergence, especially during the first 5 days.

Ungerminated/dead seeds:

Table 11 shows the effects of opener types and contrasting crop residue conditions on ungerminated or dead seeds, and the interactions between these two parameters. From the Table, there appeared to be a significantly (P<0.01) larger number of ungerminated/dead seeds in the grooves of the triple disc opener (32.9%) compared with the grooves of

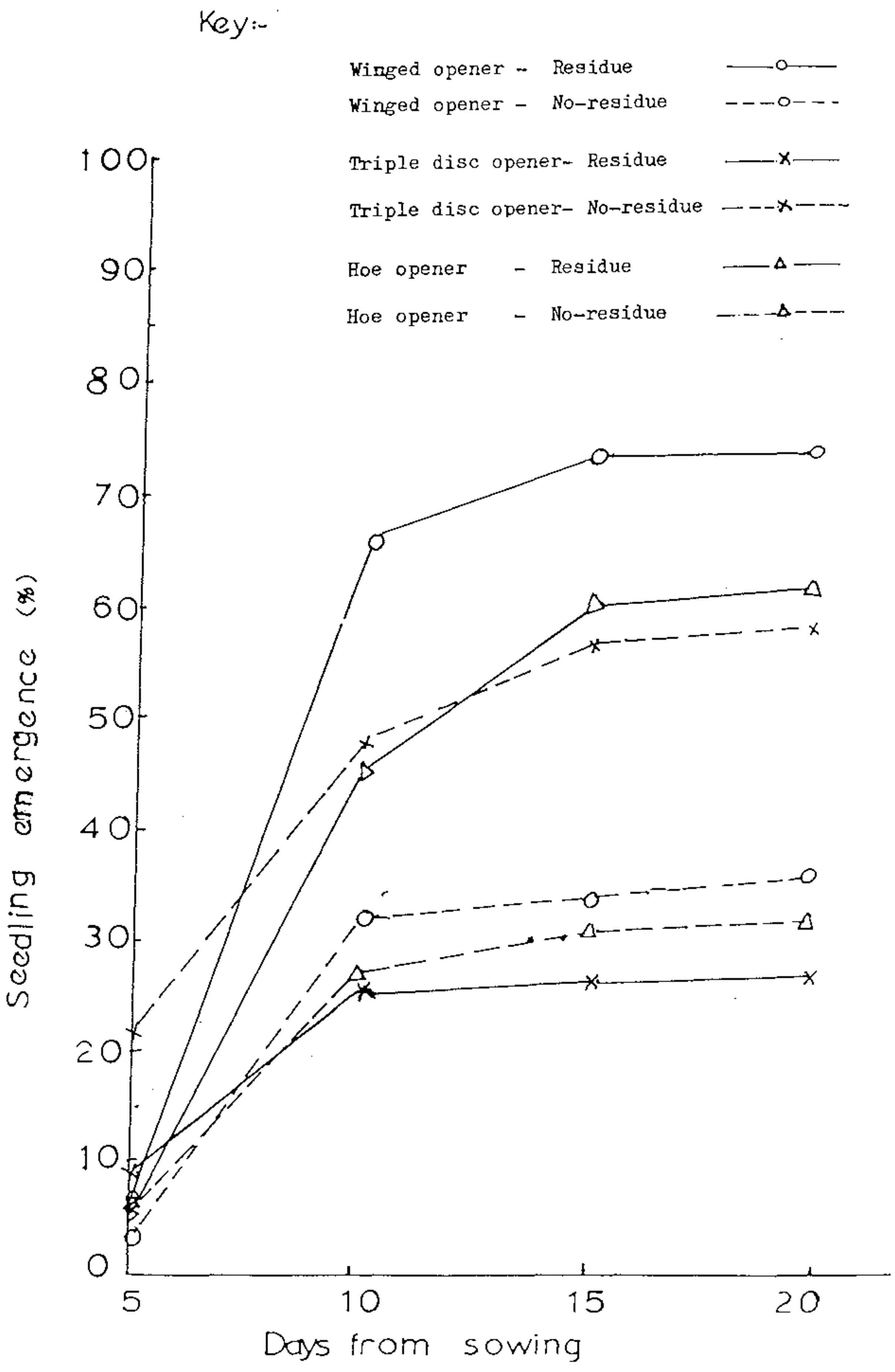


Figure 19: Effects of direct drilling opener types and contrasting crop residue conditions, on seedling emergence rates of barley, under temporary high water table conditions.

winged (17.8%) or hoe (21.6%) openers, which were not significantly different.

The contrasting surface residue conditions appeared to have no significant effects on the numbers of ungerminated or dead seeds. The reason for this may be apparent from the interactions described below.

The interactions between opener types and surface residue conditions clearly favoured the winged and hoe openers operating in residue. On the other hand, the presence of residue clearly disadvantaged the triple disc opener. This contrast between openers would undoubtedly have resulted in the non-significant overall differences between residue and no-residue noted above. The winged opener in residue actually performed better than the triple disc opener in no-residue in this experiment. As in Experiment 2, the triple disc opener alone, was seen to push residue down into the groove in contact with seeds. Again, perhaps this resulted in an adverse phytotoxic effect on seed germination as suggested by Ellis et al (1975); Lynch (1977, 1978) and Lynch et al (1980).

"Germinated but unemerged" seedlings:

Table 11 also shows the effects of opener types and contrasting crop residue conditions on "germinated but unemerged" seedlings, and the interactions between these two parameters. From the Table, there appeared to be no significant effects on the numbers of "germinated but unemerged" seedlings due to opener types . However, the contrasting crop residue conditions had a significant ($P<0.05$) effect on these counts of seedlings. Counts of such seedlings in no-residue conditions were significantly higher (30.3%) than under residue conditions (23.3%).

The interactions between opener types and surface residue conditions showed that the grooves of the winged opener responded favourably to residue. In contrast to the simulated rain conditions (Experiment 2) the behaviour of the grooves of the triple disc and hoe openers with a temporary high water table was little different under residue and no-residue conditions. It is difficult to see a logical explanation for this.

Summary of seed fate:

The collective seed fate data are shown in Figure 20. As with Experiment 2, it is apparent from the Figure that under the high temporary water table conditions, the major problem with the grooves of the triple disc opener was dead or ungerminated seeds, while the biggest problem seen with the winged and hoe opener grooves was "germinated but unemerged" seedlings. However, in all cases, emerged seedlings made up the largest counts of the three seed fate categories.

The Figure also suggests that a reasonable level of barley emergence was obtained where surface residue was present, by using either the winged or hoe openers.

Dry matter weight of roots:

Table 11 also lists the effects of opener types and contrasting crop residue conditions on dry matter weights of roots per plant, and the interactions between these two parameters. The Table shows that the weights of roots per plant were significantly ($P<0.01$) lower in the grooves of the triple disc opener (17.8 mg) compared with both the winged (23.2 mg) and hoe opener (22.0 mg) grooves, which were themselves not significantly different.

The contrasting surface residue conditions had a highly significant ($P<0.01$) effect on the root weights per plant. The mean root weight per plant across all opener types, under residue conditions (23.3 mg) was almost 20% higher than the mean root weight under no-residue conditions (19.6 mg).

The interactions showed a surprising result. It appears that the winged and hoe openers produced plants with the highest root weight of all treatments, but with the winged opener this occurred under no-residue conditions, while with the hoe opener it occurred under residue conditions. Otherwise both the hoe and triple disc opener grooves appeared to benefit from the presence of residue. It is difficult to see in what manner the winged opener benefitted from an absence of residue, especially as this contrasted with the results of the previous experiment. Accordingly, no explanation is offered, although it is

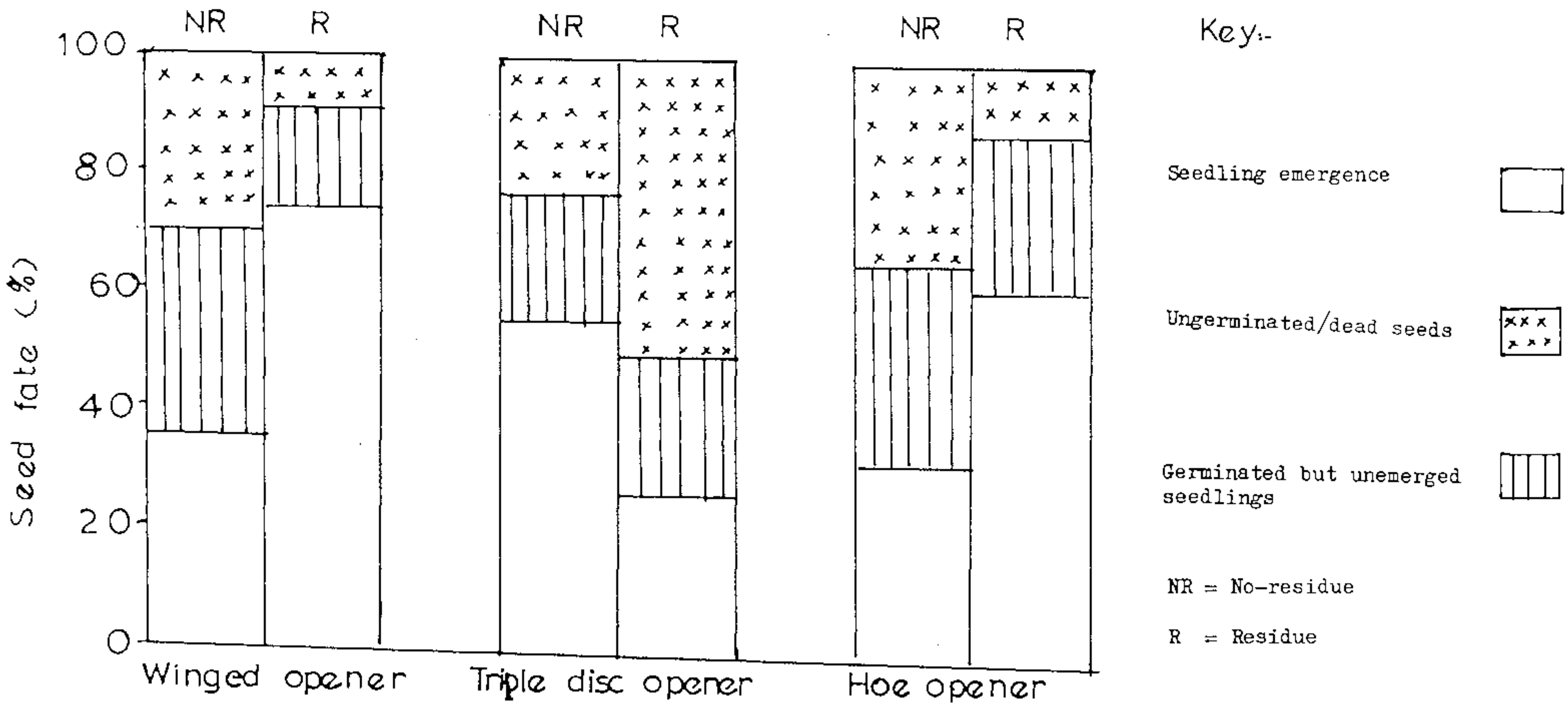


Figure 20: Effects of opener types and contrasting crop residue conditions on **cumulative** seed fate of direct drilled barley, under temporary high water table conditions.

interesting to note that even the lower of the two root weights recorded for the winged opener (under residue) probably outyielded the highest reading recorded for the triple disc opener groove.

Oxygen diffusion rate (ODR)
around the groove profiles:

Table 12 shows the effects of opener types and contrasting surface residue conditions on the ODR regimes around the groove profiles, together with the interactions between these two parameters on days 0, 5, 10, 15 and 20. It is apparent from the Table, that under the temporary high water table conditions, the effects of opener types and surface residue conditions on ODR regimes, were similar to those under simulated rain conditions. For example, on days 0 and 5 the mean ODR values of all sixteen points in the present experiment were not significantly different in the profiles around the grooves of all opener types. On day 10 the grooves created by triple disc opener showed a significantly ($P<0.05$) lower ODR regime (13.6×10^{-8} $g/cm^2/min$) compared with the regimes around the grooves of the winged (15.7×10^{-8} $g/cm^2/min$) and hoe (17.8×10^{-8} $g/cm^2/min$) openers, which were themselves not significantly different. The same trend continued through day 15 until day 20.

The contrasting residue conditions appeared to have had no significant effects on the ODR regimes on days 0 and 5, but on days 10, 15 and 20, the mean ODR of all opener types under crop residue conditions was significantly ($P<0.05$) higher than under no-residue conditions.

The interactions between opener types and suface residue conditions, on days 0-10 did not show any consistent trends. However, on days 15 and 20, all the opener types showed higher ODR regimes under residue conditions than under no-residue conditions. On days 10, 15 and 20, the ODR values associated with the winged and hoe openers were higher than those of the triple disc opener under residue conditions.

Figure 21 shows the changes in ODR regime for each opener type with time, under the contrasting crop residue conditions. The curves appeared similar to the simulated rain experiment (2). With all curves it appears that between days 0 and 5 there was a rapid reduction in the mean ODR values under both contrasting residue conditions. However, between days

Table 12: Effects of direct drilling opener types and contrasting crop residue conditions, on oxygen diffusion rate (ODR), under temporary high water table conditions.

Days from sowing	Openers			Residue		Interactions				
	Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
	ODR ($g \times 10^{-8}/cm^2/min$)									
0	49.0	51.1	50.6	50.6	49.9	NR	49.6	50.9	51.4	SED1=0.99
	Aa	Aa	Aa	Aa	Aa	R	48.5	51.3	49.8	SED2=0.62
5	19.4	19.7	19.4	19.4	19.6	NR	19.2	20.7	18.3	SED1=1.30
	Aa	Aa	Aa	Aa	Aa	R	19.6	18.8	20.5	SED2=1.32
10	15.7	13.6	17.8	14.2	17.2	NR	13.8	12.7	16.3	SED1=1.00
	Aa	Ab	Aa	Bb	Aa	R	17.6	14.6	19.2	SED2=0.35
15	15.7	14.2	15.9	13.6	16.9	NR	13.7	13.2	13.9	SED1=0.90
	Aa	Ab	Aa	Bb	Aa	R	17.7	15.3	17.9	SED2=1.08
20	15.0	13.9	15.9	13.2	16.6	NR	12.6	12.7	14.4	SED1=0.67
	Aa	Ab	Aa	Bb	Aa	R	17.5	15.1	17.3	SED2=0.66

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case $P<0.05$).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

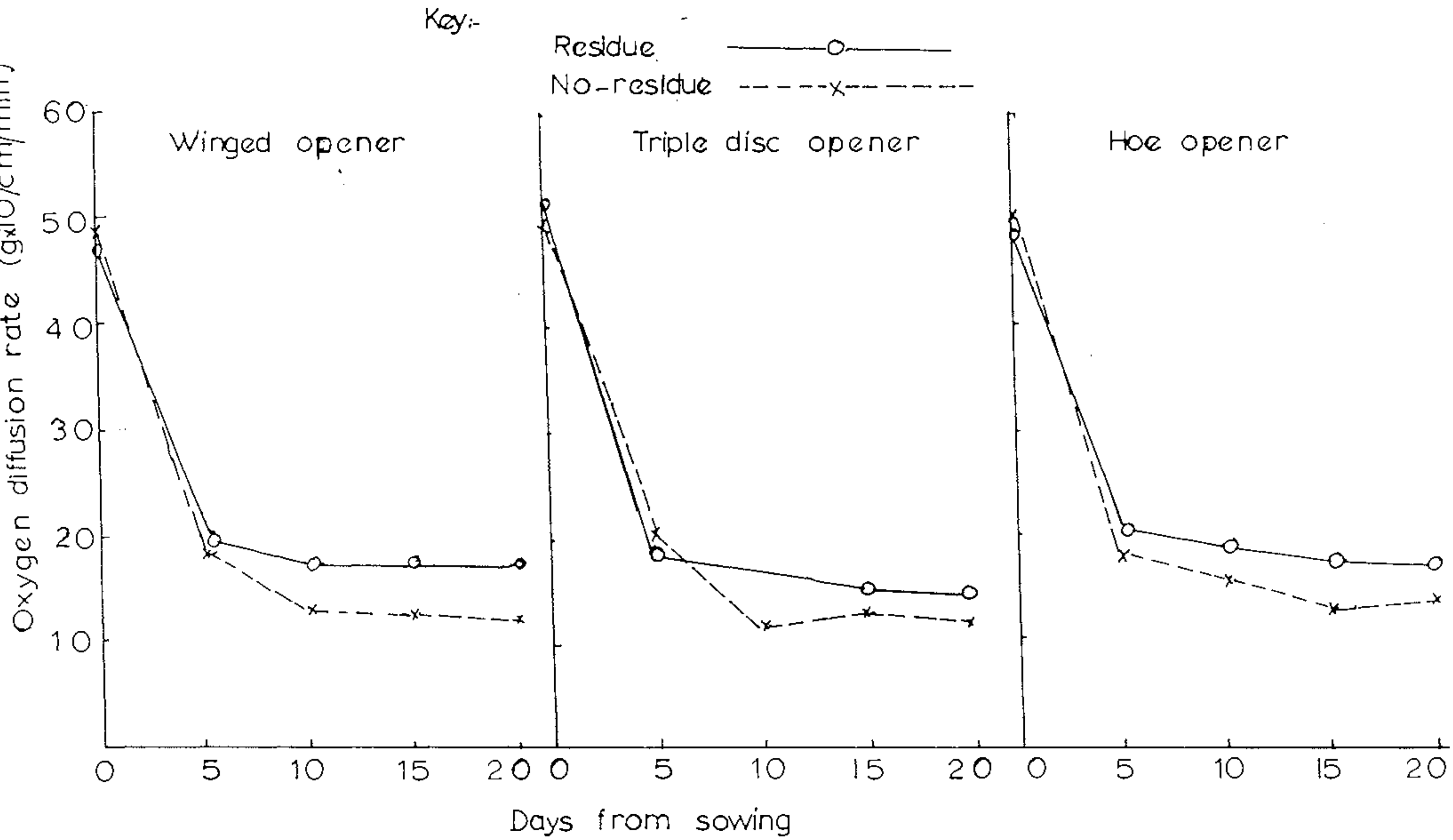


Figure 21: Effects of direct drilling opener types and contrasting crop residue conditions on changes in oxygen diffusion rate (ODR) with time, around the direct drilled grooves, under temporary high water table conditions.

5 and 20 (the terminal day), ODR regimes remained almost constant under residue conditions, but fell further under no-residue conditions.

The majority of the residue effects appeared to take place between days 5 and 10. This contrasted with the simulated rain experiment where further decline after day 5 appeared to continue, at least until day 15. The curves also illustrate that as the experiment advanced, ODR appeared to be consistently greater under crop residue conditions than under no-residue conditions.

Figures 22(a-c) are a family of iso-ODR lines which illustrate the average cumulative ODR regimes (days 5-20) for each groove and residue condition. In common with the simulated rain conditions of Experiment 2 the Figures are arbitrarily divided into the following three ODR zones; low (15×10^{-8} g/cm^2/min), medium ($15-18 \times 10^{-8}$ g/cm^2/min) and high (18×10^{-8} g/cm^2/min and above).

The Figures show that under crop residue conditions the medium ODR range extended down to 75-90 mm below the base of the grooves of the winged (Fig. 22a above) and hoe (Fig. 22c above) openers. By contrast, under no-residue conditions (Figures 22a and 22c below) with these two openers, the depth of the medium ODR zone was much shallower (35-65 mm). Both of these former openers showed large zones of high ODR immediately below and to either side of the grooves under residue conditions.

Beneath the groove of the triple disc opener the medium ODR zone extended down to 45 and 65 mm below the base of the groove, in residue (Fig. 22b above) and no-residue (Fig. 22b below) conditions respectively. However, the width of this zone was very restricted, being about 25 mm to either side of the grooves, under residue.

In contrast to the simulated rain conditions (Experiment 2) under no-residue conditions a zone of high ODR occurred near the groove of the triple disc opener. This zone extended to 35 mm below the goove base and about 25 mm on either side of the groove. This high ODR zone near the seed/soil environment may have resulted in the higher seedling emergence count recorded under no-residue conditions, that the triple disc opener showed in this experiment compared with the winged and hoe openers under similar no-residue conditions (Table 11). The occurrence of a secondary

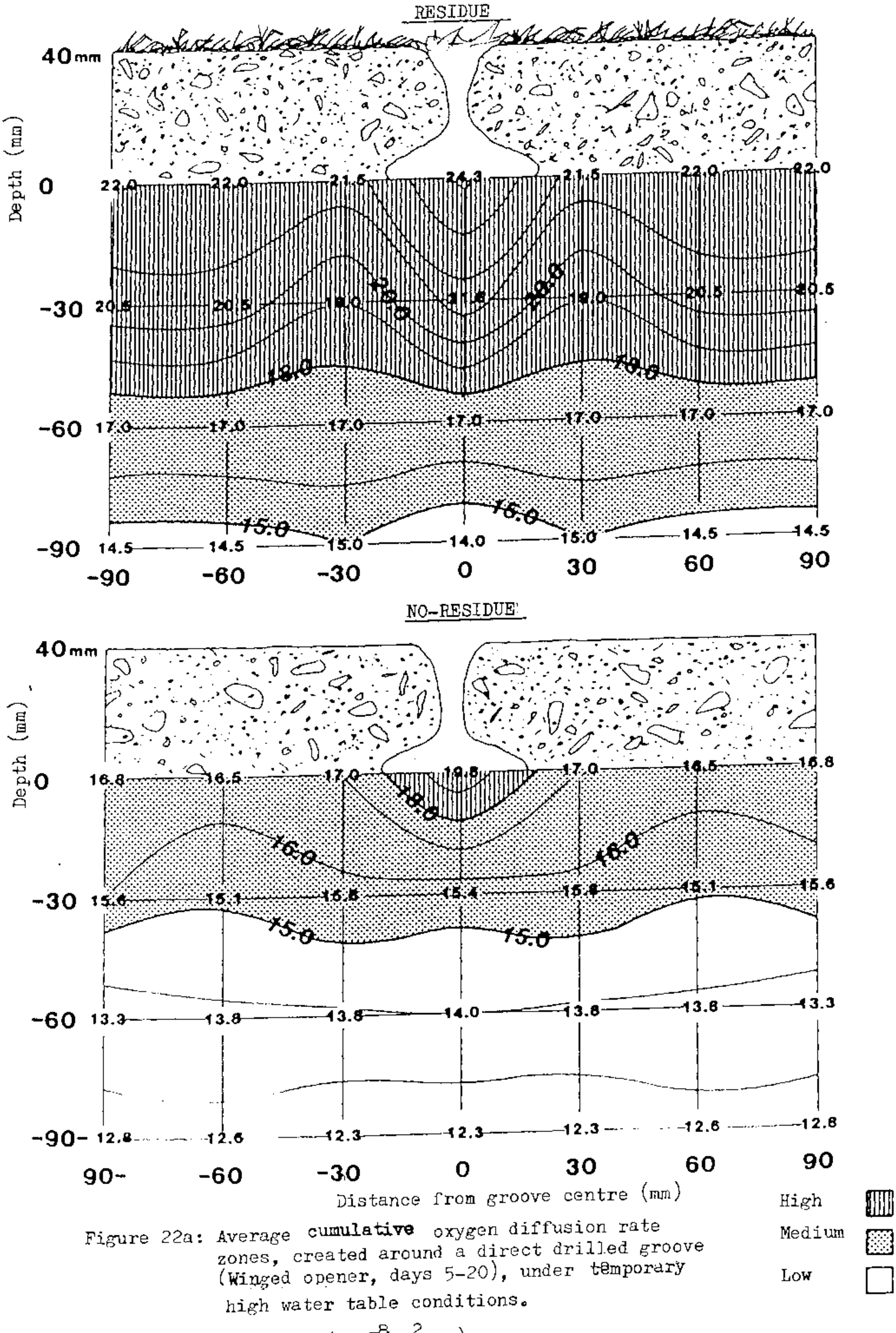


Figure 22a: Average cumulative oxygen diffusion rate zones, created around a direct drilled groove (Winged opener, days 5-20), under temporary high water table conditions.

$(g \times 10^{-8} cm^{-2} min)$

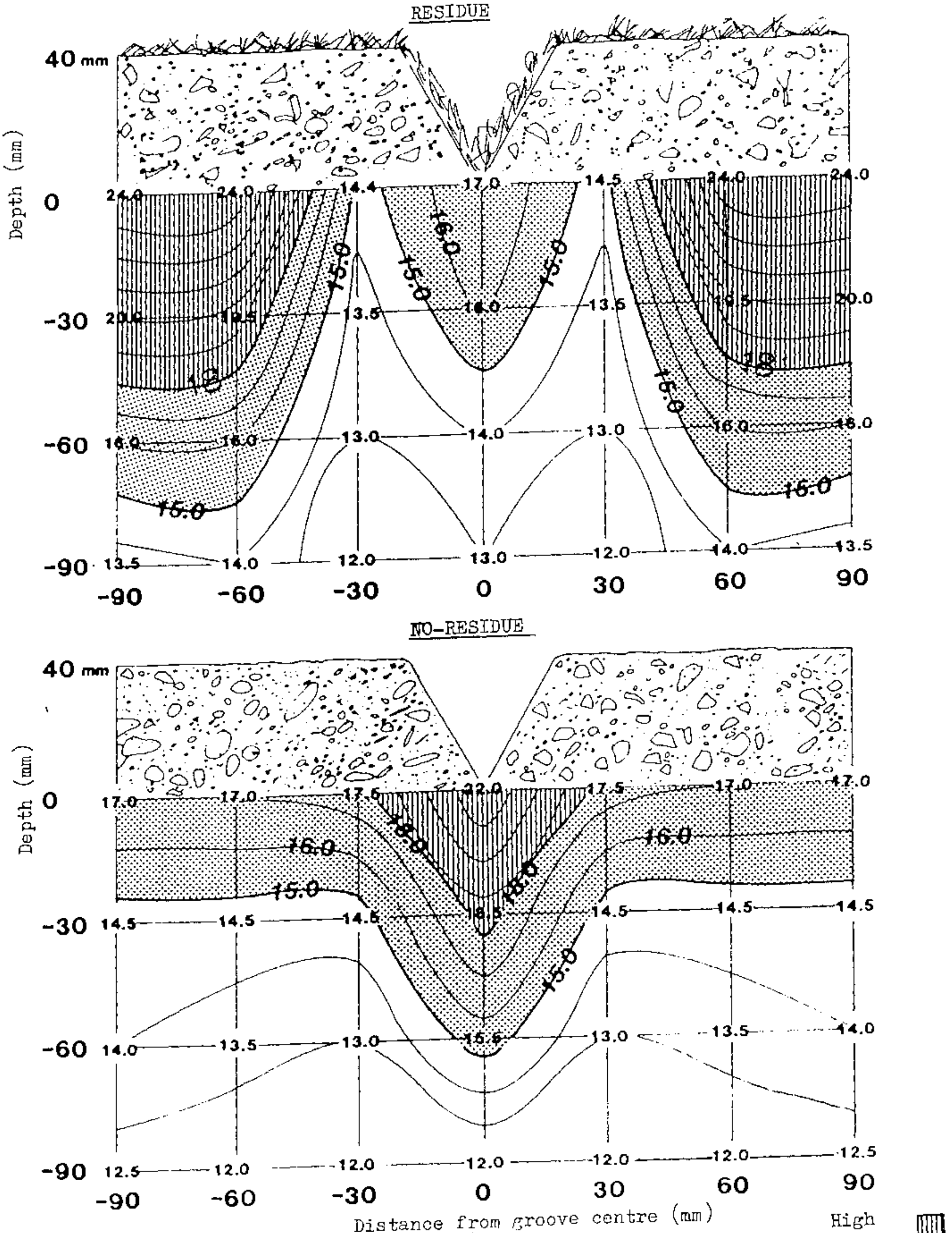


Figure 22b: Average **cumulative** oxygen diffusion rate zones, created around a direct drilled groove (Triple disc opener, days 5–20), under temporary high water table conditions.

$(g \times 10^{-8}/cm^2/min)$

High

Medium

Low

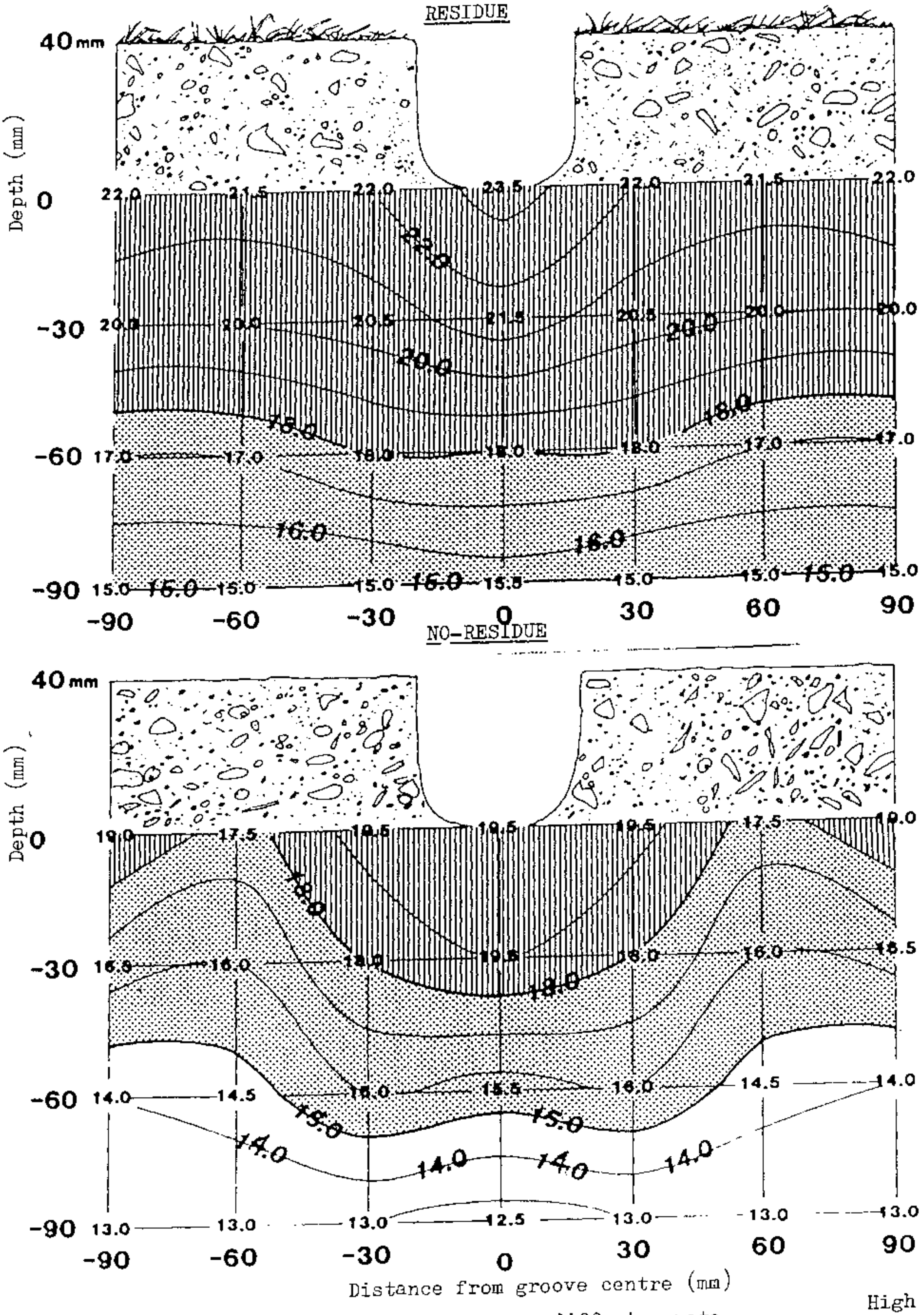


Figure 22c: Average cumulative oxygen diffusion rate zones, created around a direct drilled groove (Hoe opener, days 5-20), under temporary high water table conditions.

High
Medium
Low

$(g \times 10^{-8}/cm^2/min)$

medium ODR zone under residue conditions with the triple disc opener, was thought to be of no consequence as a 15-20 mm zone of low ODR separated the two medium ODR zones and might have been expected to seriously restrict root growth. The grooves created by the triple disc opener, under residue conditions showed no useful zone of high ODR except 50 mm to the side, which was also of little value because it too was isolated by the low ODR zone discussed above.

Earthworm populations around
the groove profiles:

Table 13 shows the effects of opener types and contrasting surface residue conditions on earthworm populations around the groove profiles, and the interactions between these two parameters. From the Table, it appears that a significantly ($P<0.01$) larger number of earthworms occurred around the groove profiles of the winged (22.0) and hoe (23.0) openers compared with those of the triple disc opener (9.7). There was no significant difference between the winged and hoe openers.

The contrasting crop residue conditions also appeared to have had a significant ($P<0.01$) effect on earthworm populations around the groove profiles. Under the residue condition the numbers of earthworms were significantly greater (23.2) than under the no-residue condition (13.2).

In common with the simulated rain conditions of Experiment 2, the interactions between opener types and surface residue conditions showed that even under residue conditions earthworms were less attracted to the grooves of the triple disc than to either the hoe or winged opener grooves without residue. As expected, the grooves of the latter two openers attracted the greatest number of earthworms of all treatments when residue was present.

In-groove soil temperature:

Table 14 shows the effects on mean in-groove soil temperature, of opener types and contrasting surface residue conditions and the interactions between these two parameters. From the Table, there appeared to be no significant ($P<0.05$) effects on in-groove soil temperature which were attributable to opener types. These findings were

Table 13: Effects of direct drilling opener types and contrasting crop residue conditions, on earthworm populations around the groove profiles, under temporary high water table conditions.

Openers			Residue		Interactions				
Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
Populations (numbers per core***)									
22.0	9.7	23.0	13.2	23.2	NR	15.0	8.7	16.0	SED1=2.18
Aa	Bb	Aa	Bb	Aa	R	29.0	10.7	30.0	SED2=1.97

Table 14: Effects of direct drilling opener types and contrasting crop residue conditions, on in-groove soil temperature, under temporary high water table conditions.

Openers			Residue		Interactions				
Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
Temperature (°C)									
19.4	19.3	19.3	19.1	19.6	NR	19.2	19.1	19.1	SED1=0.22
Aa	Aa	Aa	Bb	Aa	R	19.7	19.5	19.6	SED2=0.14

*NR = No surface residue present.
**R = Surface residue present.
***Core = 1.13 litres volume.
Unlike letters in a row denote significant differences (upper case, P<0.01; lower case P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

similar to those obtained under dry soil conditions by Baker (1976) and Choudhary (1979).

On the other hand, as had occurred under the simulated rain conditions of Experiment 2, the contrasting surface residue conditions had a small (0.5 ^{o}C) but a highly significant (P<0.01) effect on the mean in-groove soil temperature of all opener types. This small temperature rise appeared to be consistent across all opener types, according to the interactions. As with Eperiment 2 this rise might appear inconsistent with published data for untilled seedbeds (Lal, 1976; Larson, 1970); although the present data relate to the groove area, and it is possible that a similar explanation to that outlined for the former experiment is also appropriate to this experiment.

Soil bulk density around
the groove profiles:

Table 15 shows the effects of opener types and contrasting surface residue conditions on the soil bulk density regimes around the groove profiles, and the interactions between these two parameters. From the Table, there appeared to be significant (P<0.05) differences in soil bulk densities, as a function of opener types on day 0. The grooves of the triple disc opener showed a small but significantly higher soil bulk density (1.08 g/cm^{3}) than the grooves of the winged (1.06 g/cm^{3}) and hoe (1.06 g/cm^{3}) openers, which themselves were not significantly different. The higher bulk density around the grooves of the triple disc opener (compared with, at least, the winged opener) had been noted earlier by Mai (1978). Similar bulk density trends to those on day 0, were continued on days 10 and 20. However, on the intermediate reading of day 5 the grooves of the winged opener, and on day 15 the grooves of the hoe opener, recorded significantly (P<0.05) the lowest soil bulk densities of all opener types respectively. The grooves of the triple disc opener showed significantly (P<0.05) the highest soil bulk density of all opener types on all sampling days. It is difficult to see any logical reason for the reversal of the ranking of the winged and hoe openers on days 5 and 15 compared with almost all other readings, as no significant differences in earthworm activity had occurred between those two openers.

The contrasting crop residue conditions appeared to have had no

Table 15: Effects of direct drilling opener types and contrasting crop residue conditions, on soil bulk density around the groove profiles, under temporary high water table conditions.

Days from sowing	Openers			Residue		Interactions				
	Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
	Soil bulk density (g/cm^3)									
0	1.06	1.08	1.06	1.07	1.06	NR	1.06	1.09	1.06	SED1=0.10
	Ab	Aa	Ab	Aa	Aa	R	1.05	1.08	1.05	SED2=0.12
5	1.09	1.16	1.11	1.13	1.12	NR	1.11	1.16	1.12	SED1=0.016
	Ac	Aa	Ab	Aa	Aa	R	1.07	1.17	1.10	SED2=0.0134
10	1.13	1.19	1.14	1.18	1.12	NR	1.17	1.21	1.18	SED1=0.012
	Bb	Aa	Bb	Aa	Bb	R	1.09	1.17	1.10	SED2=0.010
15	1.17	1.20	1.15	1.20	1.14	NR	1.20	1.22	1.18	SED1=0.012
	Ab	Aa	Ac	Aa	Bb	R	1.14	1.17	1.11	SED2=0.013
20	1.16	1.18	1.15	1.19	1.14	NR	1.19	1.21	1.19	SED1=0.01
	Ab	Aa	Ab	Aa	Bb	R	1.13	1.16	1.12	SED2=0.01

*NR = Surface residue present.
**R = No surface residue present.
Unlike letters in a row denote significant differences (upper case, P<0.01; lower case P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

significant effects on soil bulk densities on days 0 and 5. However, on days 10, 15 and 20, as in the simulated rain conditions of Experiment 2, the soil mean bulk density, across all the opener types, under crop residue conditions was significantly ($P<0.01$) lower than under no-residue conditions.

The interactions between opener types and surface residue conditions appeared in the main to confirm the main and subtreatment effects.

Soil moisture content around
the groove profiles:

The experiment was started at average soil moisture contents (at 40-mm depth) of approximately 21.5% (d.b.) and 24.5% (d.b.) for the no-residue and surface conditions respectively. Soil moisture contents were taken from around the groove profiles at the same sixteen points as those used for soil bulk density measurements and were recorded on days 0, 5, 10, 15 and 20.

Table 16 shows the effects of opener types and contrasting surface residue conditions on soil moisture contents around the groove profiles, and the interactions between these two parameters. It appears from the Table, that on days 0, 5 and 20 there were no significant ($P<0.05$) differences in soil moisture contents around the groove profiles, as a function of opener types. However, on day 10, the grooves of hoe opener showed a significantly ($P<0.05$) lower soil moisture content (31.8%) compared to the grooves of the winged (33.7%) and triple disc (34.4%) openers, which were themselves not significantly different. By contrast, on day 15 the grooves of the winged opener (33.3%) showed a significantly lower soil moisture content than the grooves of the triple disc (34.1%) and hoe (33.8%) openers. On day 10, perhaps the lower soil moisture content around the groove profile of the hoe opener, reflected the more open (drying) nature of this groove, compared with the closed (winged) or narrower (triple disc) grooves. However, it is difficult to see any logical reason for the reversal of ranking of the winged and hoe openers on day 15, compared with almost all other readings, especially on day 10.

The contrasting surface residue conditions had a significant effect ($P<0.05$) on all days except days 5 and 15. As expected, on day 0 the

Table 16: Effects of direct drilling opener types and contrasting crop residue conditions, on soil moisture content around the groove profiles, under temporary high water table conditions.

Days from sowing	Openers			Residue		Interactions				
	Winged	triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
	Soil moisture content (%d.b)									
0	23.7	23.7	24.0	23.2	24.4	NR	23.0	23.1	23.4	SED1=0.14
	Aa	Aa	Aa	Bb	Aa	R	24.4	24.3	24.5	SED2=0.15
5	30.8	31.2	31.3	30.7	31.5	NR	30.5	30.3	31.3	SED1=0.51
	Aa	Aa	Aa	Aa	Aa	R	31.1	32.2	31.4	SED2=0.61
10	33.7	34.4	31.8	33.8	32.7	NR	34.6	34.6	32.2	SED1=0.43
	Aa	Aa	Bb	Aa	Bb	R	32.7	34.3	31.3	SED2=0.37
15	33.3	34.1	33.8	34.0	33.6	NR	33.5	34.2	34.3	SED1=0.48
	Ab	Aa	Aa	Aa	Aa	R	33.2	34.0	33.4	SED2=0.65
20	35.5	34.9	34.6	35.6	34.4	NR	36.4	35.2	35.2	SED1=0.38
	Aa	Aa	Aa	Aa	Bb	R	34.6	34.7	34.1	SED2=0.39

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote significant differences (upper case, P<0.01; lower case, P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

crop residue conditions (24.4%) showed a significantly higher soil moisture content than the no-residue conditions (23.2%). As with the simulated rain experiment (2), on day 10 and 20 the soil moisture contents under no-residue conditions were significantly ($P<0.01$) higher than under residue conditions. No logical reason could be seen to explain the higher soil moisture contents in the absence of residue, except in the latter part of the experiment, where earthworm activity might have been lower under the no-residue condition, creating fewer channels for drying air.

The interactions appeared to confirm that the trends of the main and subtreatments, had applied to the winged and hoe openers, but that trends were inconsistent with the triple disc opener.

3.2.6 Discussion of Experiments 2 and 3

The most noteworthy aspect of these two experiments was that the treatment effects were mainly clear and the differences relatively large. Furthermore, the trends recorded were remarkably similar in the two experiments, regardless of whether soil saturation had been caused by simulated intermittent rainfall or intermittent high water table conditions. Thus, any possible effects of rain-drop splash on exposed soil surfaces or grooves appears to have had a negligible influence on seed or seedling survival.

The results of these two experiments also indicated that the effects the major treatments (opener types and crop residue conditions) had on physical parameters (ODR, soil bulk density and soil moisture content) and biological parameters (seedling emergence) occurred after day 5. For example, measurements of physical and biological parameters up to day 5 showed either little or no significant differences in opener types or contrasting crop residue conditions. This suggests that under wet soil conditions, the soil parameters responsible for influencing seed fate were only affected over a period of time.

Under both the simulated high rainfall and temporary rising water table conditions, there had been greater seedling emergence and root weights per plant where the winged and hoe openers had been used, compared with the triple disc opener, particularly under surface residue conditions. The grooves created by the triple disc opener resulted in the lowest counts of seedlings, and the lowest root weights per plant of the three openers tested. The differences between openers, in terms of seedling performances and root weights per plant, were greatest under surface residue conditions. At least part of the reason for this might have been that the triple disc opener had been observed to push residue down into the seed groove, and the resulting contact with the seed under wet conditions might have produced phytotoxic effects of decomposing crop residue on seed germination and seedling growth. By contrast, it was observed that the winged and hoe openers did not push crop residue into the seed grooves. The hoe opener swept it aside and the winged opener left it in place on the soil surface, and opened the groove mainly from beneath the residue. With this opener seeds were at no time in direct contact with decomposing crop residue.

In these experiments under residue conditions, it was also found that a significantly higher number of dead seeds (59.8%) accumulated in the grooves of the triple disc opener than in those of either the winged (7.4%) or hoe (17.8%) openers. This adds further support to the possibility of phytotoxic seed mortality, although no attempt was made to measure the existance of phytotoxic substances in these experiments.

The second determinant which appeared to affect seed fate was oxygen diffusion rate (ODR) in the soil zone around the grooves. From the ODR analyses it appears that soil around the grooves created by the triple disc opener produced significantly the lowest ODR regimes, both under crop residue and no-residue conditions, compared to soil around the grooves formed by the winged and hoe openers. Barley seeds and seedlings apparently had a high tolerance of low soil oxygen and were able to grow roots at an ODR value as low as 15×10^{-8} $gm/cm^2/min$ (Letey et al, 1962b), although no specific data were available for a Tokomaru silt loam soil. From Table 6 it is apparent that while the mean ODR around the grooves of the triple disc opener approached this range on occasions, on most of the measuring dates it was lower than the minimum requirements reported for barley. This was clearly reflected in poor seed/seedling performance. On the other hand, the grooves of both the winged and hoe openers produced extensive zones of high ODR close to the seed, especially under residue.

The importance of a low ODR regime near the grooves of the triple disc opener, compared with the other openers, was supported by measurements of other soil determinants such as bulk density and soil moisture content, together with the extent of earthworm activity. The soil around the grooves of the triple disc opener recorded a significantly higher bulk density compared with both of the other two openers. Many authors have reported a relationship between high soil bulk densities and reduced ODR values (Bertrand and Kohnke, 1957; Taylor, 1949; Raney, 1949). Another author has noted that factors, such as soil moisture content and the shape of the soil particles could also be important (Taylor, loc cit).

There have been numerous reports in the literature that earthworm channels could increase the path of gaseous exchange into the soil (Barley, 1959; Edwards and Lofty, 1977). In the experiments reported here, the earthworm populations in the soil surrounding the grooves of the triple disc opener were significantly lower than around the grooves of either the winged or hoe openers. It is possible that this could have affected the ODR regimes in these zones and thus have had an indirect effect on seedling growth and/or survival. In this respect, iso-ODR lines drawn around the grooves of the triple disc opener clearly indicated that these grooves were only marginally able to meet the minimum range of ODR required for barley near the seed micro-environments, compared with the more favourable situations for the winged and hoe openers.

The contrasting surface residue conditions had significant effects on earthworm populations. It was clear from the data that earthworm populations under crop residue conditions were almost double those under no-residue conditions. Similar effects have been reported by several authors (Edwards and Lofty, 1972,1975; Lal, 1976). These earthworm populations might have affected soil aeration around the grooves, and thus have indirectly affected seed germination and seedling growth.

The results of these two experiments suggest a need to study the influence of opener types on seed germination and seedling growth in the presence and absence of earthworms and in the presence and absence of crop residue. Both the experiments described had suggested indirect effects of surface residue and earthworm activity on seed fate. It was possible that opener types could have interacted with both earthworms and residue in influencing these results.

3.3 EFFECTS OF CARBARYL ON EARTHWORMS, SEEDS AND SEEDLINGS IN A WET SOIL

3.3.1 Introduction:

In order to study the effects of the presence or absence of earthworms on seed germination and seedling emergence and the seed/soil environment around a direct drilled groove (see Experiments 7, 8 and 9 later), pilot experiments were conducted to develop a suitable procedure for killing earthworms. A set of three pilot experiments was conducted to quantify the effects of carbaryl on the mortality of the earthworms, and possible toxic effects on barley seed germination and seedling growth. The pilot experiments are outlined below in Sections 3.3.2, 3.3.3 and 3.3.4.

3.3.2 Effect of carbaryl on the mortality of earthworms:

(Pilot experiment, Experiment 4)

(a) Objectives:

The objectives of this experiment were to study the effects of solutions of carbaryl applied to the soil surface on the mortality of earthworms and to identify the populations of different earthworm species with respect to their depth in the soil.

(b) Materials and methods:

An area in the experimental field (on a Tokomaru silt-loam soil) was sprayed with 2 kg/ha a.i. carbaryl in 3000 ppm water dilution, while a similar area was left unsprayed. After day 3, two core soil samples of 100 mm in diameter and 200 mm deep were collected from each area. These were cut into two depths of 0-100 mm and 100-200 mm in order to count the numbers of earthworms within each depth zone. This pilot experiment was not replicated as it was designed only to note any major effect of carbaryl which would need to be examined in more detail at a later date.

(c) Results and discussion:

Table 17 shows the earthworm populations (in two depth zones 0-100 mm and 100-200 mm) and earthworm species after day 3 in the sprayed and unsprayed plots. From the Table it appears that at day 3 there had been only a slight reduction in earthworm numbers in the sprayed area, but those earthworms that had survived appeared all to be in poor condition and did not appear to be feeding. They appeared to be inactive.

At day 7, there was about 80% mortality of earthworms in the sprayed plots. Furthermore, during the total experimental period of 20 days no earthworm casts or holes were observed on the soil surface of the pots collected from the sprayed plots. This suggested that earthworm activity, if not mortality, completely stopped, which was confirmed by final counts of earthworms in all the pots on day 20. This was later confirmed in Experiment 7 (see Tables 22 and 23).

Table 17 has shown that in the experimental field only three species of earthworms were present. These were Allolobophora longa (Ude), Allolobophora caliginosa (Sav) and Lumbricus rubellus (Hoff). All three species were mostly active on the top soil of 0-100 mm depth, although Janson (1984) showed that Lumbricus rubellus was more likely to be active in the direct drilled zone than Allolobophora caliginosa.

Table 17: Earthworm populations in Tokomaru silt-loam soil, 3 days after spraying carbaryl.

Area	Depth from soil surface	Earthworm species/ Grand totals	*A. longa*			*L. rubellus*			*A. caliginosa*		
			total	M*	J**	Total	M	J	Total	M	J
		Populations (numbers per core***)									
A	0-100mm	91	25	10	15	38	13	25	28	19	9
	100-200mm	8	2	1	1	5	2	3	1	1	-
	0-200mm	99	27	11	16	43	15	28	29	20	9
B	0-100mm	126	39	7	32	46	10	36	41	10	31
	100-200mm	4	3	2	1	1	1	-	-	-	-
	0-200mm	130	42	9	3	47	11	36	41	10	31

*M = Mature
**J= Juvenile
***Core volume = 0.8 litres
A= Area sprayed with carbaryl at the rate of 2 kg/ha a. i.
B= Unsprayed area.

3.3.3 Effects of carbaryl on roots and shoots of barley sown in soil (Pilot experiment, Experiment 5).

(a) Objectives:

Little information on the possible effects of carbaryl on seed germination or seedling growth of barley was available from the literature. A pilot experiment was, therefore, designed to study these effects with barley (variety Magnum) sown in soil in a glasshouse.

(b) Materials and methods:

Carbaryl was sprayed onto the undisturbed surface of field plots at two rates; 2 kg/ha a.i. and 3 kg/ha a.i, both in an aqeous solution of 3000 and 4000 ppm respectively. A third plot was left unsprayed. Undisturbed soil samples of 160 x 160 x 200 mm size were taken from each plot and placed into plastic pots of the same size. The pots were shifted to a glasshouse and kept under simulated rain of 5 mm/hour intensity for four hours. After a further 16 hours drainage (total 20 hours) 50 seeds were sown manually at 40 mm depth in each pot by using a spatula to loosen a zone of soil and forceps to insert individual seeds. This represented a higher than normal seeding rate but was used in order to examine a reasonable seed sample size in the small pots. In the pots, placement of such a number of seeds resulted in considerable surface disturbance, but this was not thought to be important in an experiment conducted in an adequate moisture regime. The field plots, from which pot samples were collected, were arranged in a completely randomised block with three replicates. The sample pots were arranged in the glasshouse in a similar experimental design. Irrigation water was applied as required to maintain the soil moisture regime in the "available" range. Terminal seedling emergence counts and root/shoot weights were obtained after 15 days.

(c) Results and discussion:

Table 18 shows the effects of the two rates of carbaryl on seed germination, seedling growth and root/shoot weights. It appears from the Table that the effects of carbaryl on seed germination and seedling emergence was negligible and certainly not significant. Seedling emergence for the control treatment was 95.4% while the 2.00 kg/ha a.i. carbaryl was 96.6% and the 3.0 kg/ha a.i. carbaryl, 96%. Similarly, there were no significant effects of carbaryl on root and shoot weights of the barley seedlings. All roots and shoots in the treatments appeared to be normal.

3.3.4 Effects of direct seed/carbaryl contact on seed germination and seedling growth of barley (Pilot experiment, Experiment 6)

(a) Objectives:

In the previous pilot experiment (5), it could not be said with certainty that seed had always been in direct contact with the carbaryl solution, due to unpredictable percolation of the simulated rain and carbaryl solution, especially in the deeper soil. The main objectives of the third pilot experiment were, therefore, to examine the effects of carbaryl on seed germination and seedling growth when seeds had remained in direct contact with the carbaryl insecticide (of different concentrations) during the experimental period.

(b) Materials and methods:

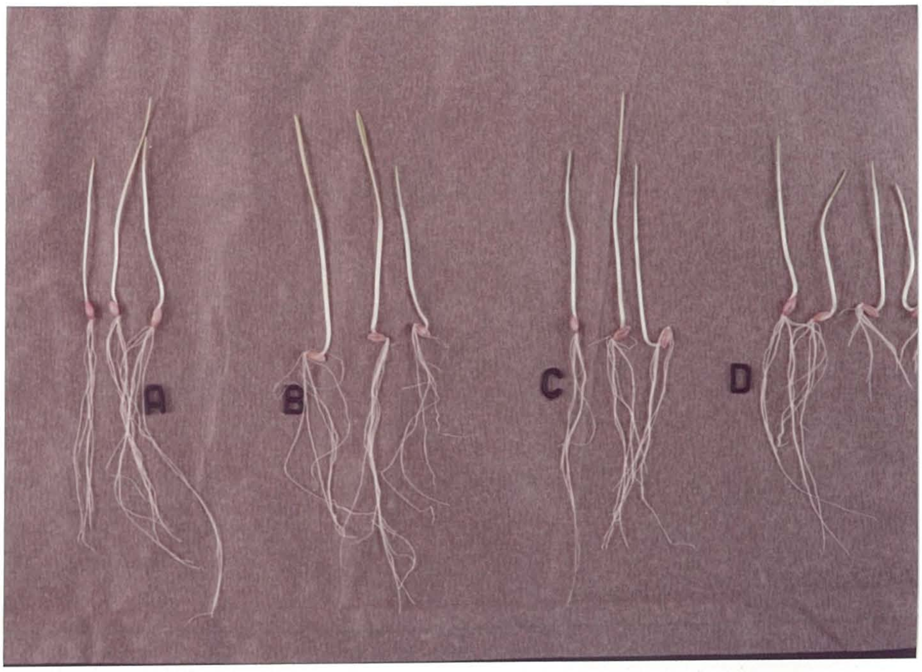
Carbaryl solutions of seven concentrations 0, 100, 1,000, 1,500, 2,000, 2,500 and 3,000 ppm were prepared and germination papers were soaked for about 5 minutes in these respective solutions. A hundred barley seeds were placed on each of the treated germination papers which

Table 18: Effect of carbaryl on seed germination and seedling growth of barley seeds, sown in undisturbed soil blocks.

Seed fate	NT*	CAR2**	CAR3***
Seedling emergence (%)	95.4	96.6	96.0
	Aa	Aa	Aa
Root weight (mg)	48.3	53.0	54.3
	Aa	Aa	Aa
Shoot weight (mg)	75.7	76.7	73.0
	Aa	Aa	Aa

* NT = Non treated.
**CAR2 = Treated with carbaryl at the rate of 2 kg/ha a. i.
***CAR3= Treated with carbaryl at the rate of 3 kg/ha a. i.

Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case $P<0.05$).



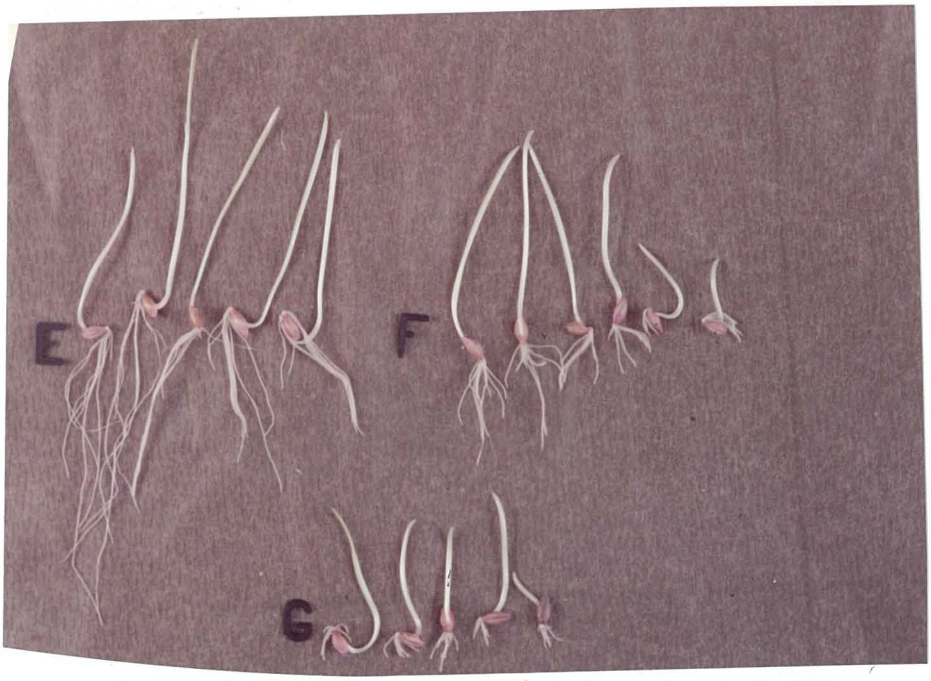


Figure 23: Effects of different concentrations of carbaryl on root/shoot development of barley.

A. Non-treated	E. 2000 ppm
B. 100 ppm	F. 2500 ppm
C. 1,000 ppm	G. 3000 ppm
D. 1,500 ppm	

Notes: 1. E, F and G are magnified more than A, B, C and D.
2. Adverse effects on root/shoot development with carbaryl solutions of 2,500 ppm and 3,000 ppm (F and G).

were wrapped and placed in a temperature controlled germination room at 20^{o} C, and 60% RH. Each treatment was replicated twice. The experiment was terminated after 15 days and the numbers of emerged seedlings counted, together with weights of roots and shoots.

(c) Results and discussions:

Table 19 shows the effects of different concentrations of carbaryl solution on seed germination and seedling growth.

It appears from the Table that the effects of different carbaryl concentrations on seedling emergence were not significantly different (P<0.05). However, the different contentrations of carbaryl had significant (P<0.05) effects on root/shoot weights. Seeds with carbaryl concentrations of 2,500 and 3,000 ppm showed the lowest root and shoot weights compared with the untreated control and concentrations of 100, 1,000 and 2,000 ppm. The root weights at 2,000 ppm solution of carbaryl were also significantly lower than the control, 100, 1,000 and 1,500 ppm solutions.

It was also observed that carbaryl solutions of 1,500 and 2,000 ppm caused root shortening and thickening types of seedling development symptomatic of toxicity. However, this effect was only temporary and these roots were later classed as normal (D. Meech, pers comm, 1983). The adverse effects of the carbaryl solution at 2,500 and 3,000 ppm were much clearer and the roots under these treatments failed to develop fully even after two weeks. They remained short and were classed as abnormal. Figure 23 illustrates the effects of different concentrations of carbaryl on seed/seedling performance of barley placed on germination paper.

3.3.5 Discussion of pilot experiments (Experiments 4, 5 and 6)

The results of the pilot experiments indicated that carbaryl sprayed onto the soil at the rate of 2.0 kg/ha a.i. (in a solution of 3,000 ppm) was effective in killing earthworms and that the effect was similar on all of the earthworm species present in the Tokomaru silt-loam soil.

Table 19: Effects of concentration of carbaryl solution on seed germination and seedling growth of barley, on germination paper.

Carbaryl solution Concentrations/ Seed fate	0.0 ppm	100 ppm	1000 ppm	1500 ppm	2000 ppm	2500 ppm	3000 ppm
Seedling emergence (%)	92.5 Aa	91.5 Aa	93.0 Aa	88.0 Aa	89.0 Aa	82.5 Aa	87.5 Aa
Root weight (mg)	8.5 Aa	8.7 Aa	9.0 Aa	8.5 Aa	7.0 Ab	3.5 Bc	2.7 Bc
Shoot weight (mg)	7.5 Aa	8.0 Aa	8.0 Aa	9.0 Aa	8.2 Aa	3.7 Bb	3.0 Bb

Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case, $P<0.05$).

It also appeared that the three earthworm species identified, were present in roughly equal numbers in the top 100 mm of soil. It was thought, therefore, that changes in the soil which occurred as a result of opener types or surface residue treatments might influence the earthworm populations in this zone. On the other hand, it was not possible to study the indirect effects of earthworms on seed fate without introducing an earthworm-free treatment. As no such natural soil was available, it was necessary to kill earthworms (in this case using carbaryl _in situ_) and also to know what the residual effects of the killing agent (carbaryl) were likely to be on seed fate. The pilot experiments indicated that carbaryl, applied to the soil at 2.0 kg/ha a.i was not toxic to seed germination or seedling growth. There were severe toxic effects on seedlings from direct seed contact with carbaryl solutions of 2,000 ppm and above, but in this respect several factors should be kept in mind.

The concentration of carbaryl in the germination papers would be higher than the final concentration in the soil as a result of irrigation, because of dilution by water and other soil solutes during infiltration and percolation.
(T. Holland, pers comm, 1983)

Seeds which had been affected, had remained continuously in direct contact with the carbaryl solution in the germination papers for two weeks.

The application of the carbaryl solution to the soil was accompanied by simulated rainfall of 20 mm before sowing the seed. It is possible therefore, that most of the carbaryl had penetrated beyond sowing depth before seeds were introduced, and its residual effects on seeds might thus have been reduced. Holland (_loc.cit_) felt that with rain water in a permeable soil, carbaryl penetrated into the deeper layers of soil, and no residual toxic effects could be observed at seed level. Carbaryl has also been considered by other workers to be non-toxic when used at rates of 0.25-2.00 kg/ha a.i. (Anon, 1979).

It was therefore felt that the results of these three pilot experiments supported the use of carbaryl at the rate of 2.0 kg/ha a.i. as a means of killing earthworms, with little or no risk of toxic effects on seed germination and seedling growth of barley in the soil.

3.4 EFFECTS OF OPENER TYPES, RESIDUE AND EARTHWORM ACTIVITY ON SEED/SEEDLING PERFORMANCE.

3.4.1 Objectives:

In the earlier experiments (1, 2 and 3) the triple disc opener appeared to have performed consistently poorly in terms of seedling emergence, earthworm populations, oxygen diffusion rates (ODR) and soil bulk density measurements around the groove profiles. Unlike the winged and hoe openers, under surface residue conditions the performance of the triple disc opener deteriorated significantly. Therefore, it was felt desirable to conduct a series of experiments to study the effects of earthworm activity and contact of seeds with decomposing crop residue, on seed germination and seedling growth.

3.4.2 Materials and methods:

Surface residue and no-residue conditions were created in the same way as for tillage bin experiments (described earlier, Experiments 2 and 3). To eliminate earthworm activity in the soil, carbaryl was sprayed at the rate of 2.0 kg/ha a.i. (on both residue and no-residue conditions), 7 days before the drilling operation. After spraying carbaryl, simulated rain conditions were activated on the first day with an intensity of 5 mm per hour for 4 hours to ensure rapid percolation of the carbaryl into the deeper soil.

Three opener types, winged, triple disc and hoe were compared. The drilling operation was performed in the field using a special tractor-drawn drilling rig, after which rectangular soil blocks measuring 160 mm x 160 mm x 200 mm were cut with a spade and placed in plastic pots of the same size.

The field plots and residue treatments were of a split-plot design with openers as the main treatments and residue conditions as subtreatments. Two separate experiments: 7 and 8 (without and with earthworms) were conducted in the same manner side by side with three replicates each. All the pots were shifted to a glasshouse and arranged in the same split-plot design. Ten seeds of barley (variety Magnum, with 95% laboratory germination) were sown manually in each treatment using forceps.

The size of the pots was small compared to the size of tillage bins. Therefore, all four sides of a soil sample in a pot were covered with molten wax before placing them in the pots. This was done to reduce possible interchange of atmospheric oxygen through the sides of the sample and its effects on oxygen diffusion rate (ODR).

Both of these experiments were conducted under simulated rain conditions (20 mm a day at an intensity of 5 mm/hour) in a glasshouse at 20-25 ^{o} C.

The following measurements were taken in both experiments.

Oxygen diffusion rate (ODR) was measured around the groove profiles using 12 points (instead of 16 as used earlier, Figure 13). The measurements were taken on days 0, 5, 10, 15 and 20. As in the tillage bin experiments the small holes of the electrodes were filled with slurry immediately after taking the measurements. Figure 24 shows a grid pattern adopted for measuring ODR regimes around the groove profiles.

No detailed soil bulk density measurements were taken during the experimental period, because such measurements were destructive, and there was insufficient room within these small pots to allow for destructive sampling. Therefore, soil bulk density and soil moisture content measurements were taken in the general soil matrix on the final day (day 21).

Seedling emergence, seed fate counts and root weights were taken.

Earthworm populations and species were counted on the

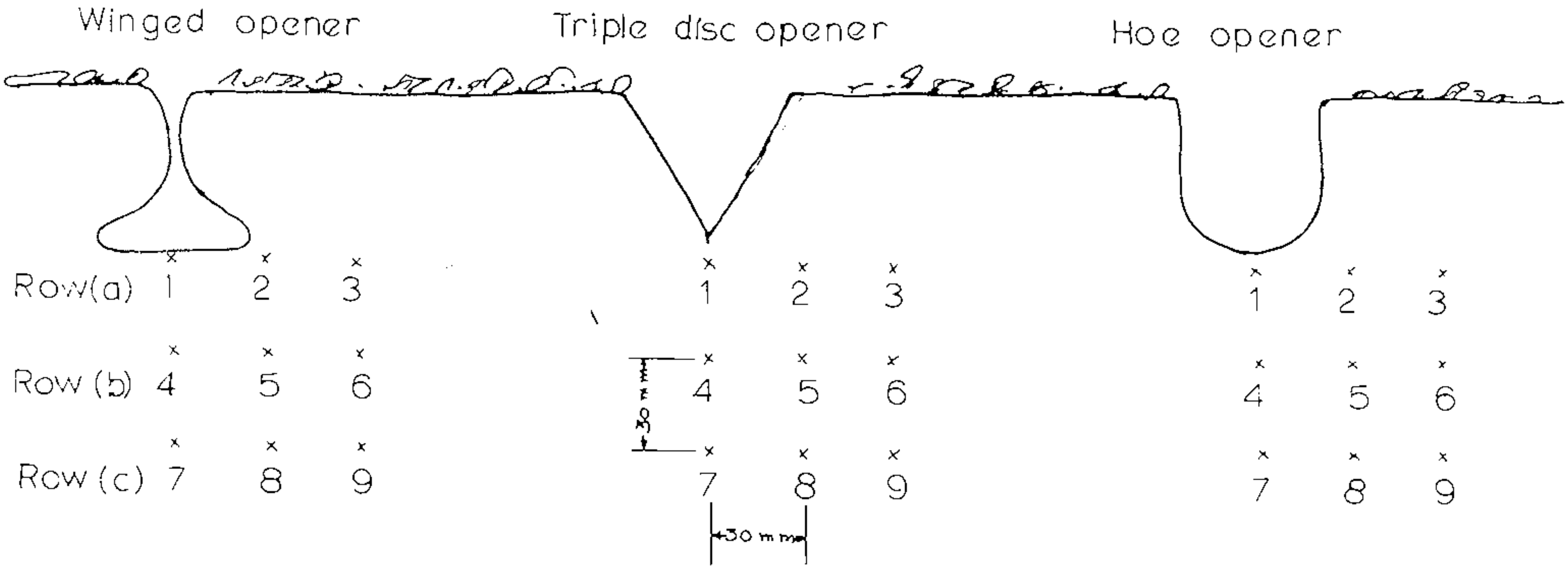


Figure 24: The grid pattern for measuring oxygen diffusion rate (ODR), around direct drilled grooves, in the presence and the absence of earthworms, under simulated rain conditions (Experiments 7 and 8).

last day.

3.4.3 Results and discussion:

(a) Experiment 7 (absence of earthworms):

Seedling emergence:

Table 20 shows the effects of opener types and contrasting surface residue conditions on seedling emergence and seed fate of the direct drilled seeds in the absence of earthworms, and the interactions between these parameters. From the table there were no significant differences ($P<0.05$) in seedling emergence percentage amongst opener types.

Similarly, there were no significant effects of contrasting surface residue conditions on seedling emergence.

The interactions showed that there was lower seedling emergence from the grooves of the triple disc opener in residue compared with those of the winged and the hoe openers in no-residue. The low emergence from the grooves of the triple disc opener might have been due to the phytotoxic effects of the decomposition of the crop residue as earlier described in Section 3.2.

Ungerminated/dead seeds:

Table 20 also lists the effects of opener types and contrasting crop residue conditions on ungerminated/dead seeds, and the interactions between these two parameters. From the Table, there appeared to be no significant effects of opener types on the percentage of ungerminated or dead seeds. However, the contrasting surface residue conditions had a highly significant ($P<0.01$) effect on the numbers of ungerminated/dead seeds across all opener types. The presence of surface residue appeared to cause a higher number of ungerminated (38.9%) seeds than the no-residue conditions (29.8%).

Table 20: Effects of opener types and contrasting crop residue conditions, on the fate of direct drilled barley seeds, in the absence of earthworms, under simulated rain conditions.

Seed fate	Openers			Residue		Interactions				
	Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
Seedling emergence (%)	56.7	46.7	58.3	58.9	48.9	NR	63.3	53.3	60.0	SED1=15.15
	Aa	Aa	Aa	Aa	Aa	R	50.0	40.0	56.7	SED2= 9.43
Ungerminated or dead seeds (%)	33.0	40.8	29.2	29.8	38.9	NR	29.3	33.3	26.7	SED1=10.18
	Aa	Aa	Aa	Bb	Aa	R	36.7	48.3	31.7	SED2= 3.72
Germinated but unemerged seedlings (%)	10.3	12.5	12.5	11.3	12.2	NR	7.3	13.3	13.1	SED1= 4.54
	Aa	Aa	Aa	Aa	Aa	R	13.2	11.3	11.7	SED2= 4.41
Dry matter weights of roots (mg)	7.1	7.3	6.5	7.2	7.2	NR	7.4	8.1	6.2	SED1= 1.5
	Aa	Aa	Aa	Aa	Aa	R	8.3	6.5	6.9	SED2= 1.0

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote significant differences (upper case, P<0.01; lower case, P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

The interactions between opener types and surface residue conditions showed that the use of the triple disc opener in residue may have resulted in higher counts of dead or ungerminated seeds than either of the other opener/residue combinations. Perhaps this again reflected the adverse effect of seed/residue contact on germination under wet soils as discussed earlier, although the comparison between the triple disc opener with and without residue was less marked than the comparison between this opener with residue and the other openers without residue.

"Germinated but unemerged" seedlings.

Table 20 also shows the effects of opener types and contrasting crop residue conditions, on "germinated but unemerged" seedlings, and the interactions between these two parameters.

The Table shows that there were no significant effects of opener types on the percentage of "germinated but unemerged" seedlings. Similarly, the contrasting surface residue conditions had no significant effects on "germinated but unemerged" seedlings.

The interactions showed no differences amongst treatment combinations.

Summary of seed fate:

Figure 25 shows the rate of seedling emergence in the absence of earthworms under surface residue and no-residue conditions. The more open grooves (eg, hoe and triple disc) appeared to promote more rapid initial emergence (from days 5 to 10) than the closed grooves of the winged opener, even although these early trends did not necessarily reflect total emergence over a longer period. All openers, except the winged opener either plateaued about that time or at least declined in their rates of further emergence.

Figure 26 shows the overall effects of opener types and crop residue conditions on seed fate. It is apparent that with all openers the major problem was dead or ungerminated seeds, and that this was more important in the absence of surface residue.

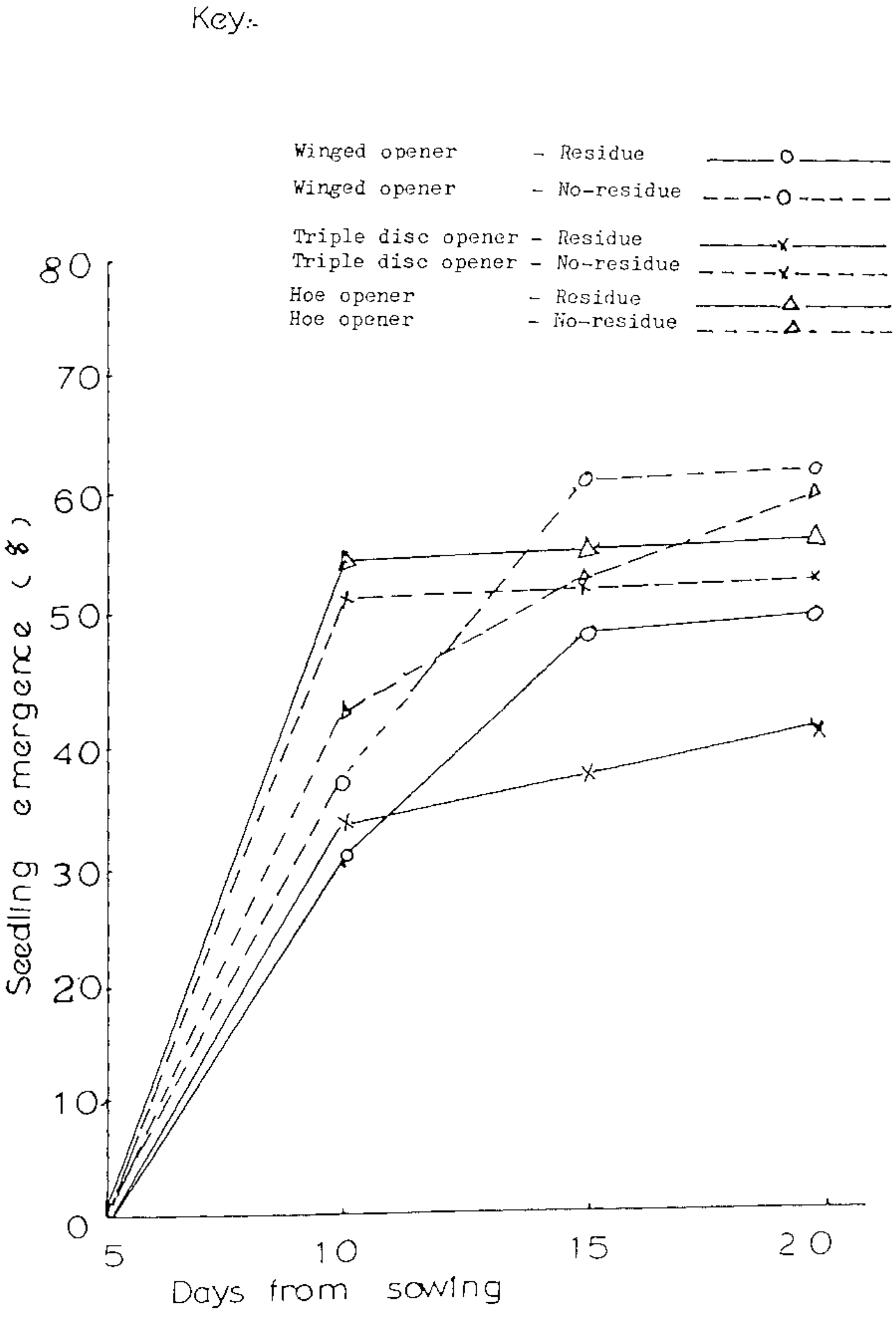


Figure 25: Effects of direct drilling opener types and contrasting crop residue conditions, on seedling emergence rates of barley, in the absence of earthworms, under simulated rain conditions.

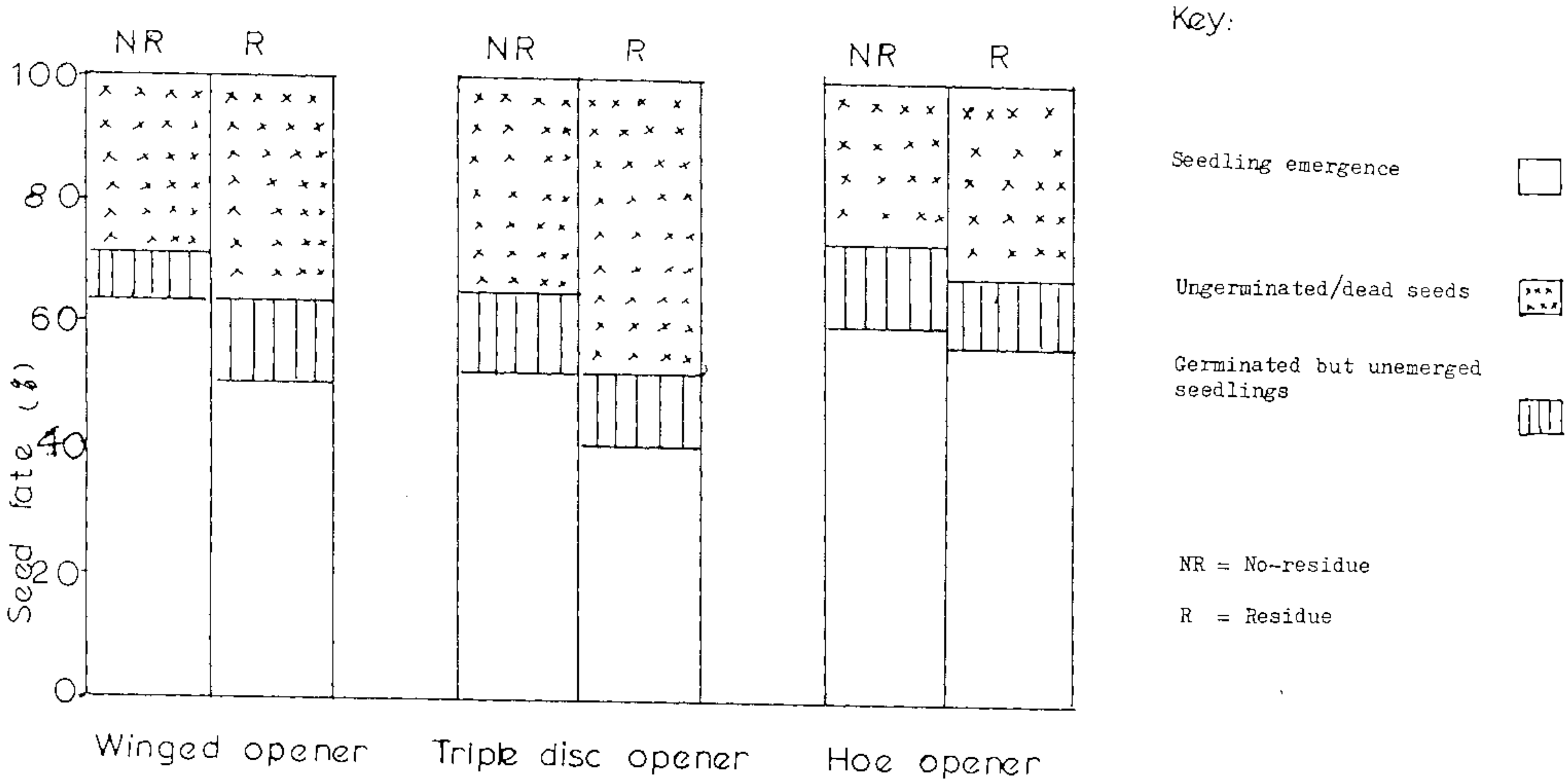


Figure 26: Effects of opener types and contrasting crop residue conditions on **cumulative** seed fate of direct drilled barley, in the absence of earthworms, under simulated rain conditions.

Dry matter weight of roots:

Table 20 also lists the effects of opener types and contrasting crop residue conditions, on root weights per plant, and the interactions between these two parameters. The Table shows no significant effects of opener types or contrasting surface residue conditions on the dry matter weight of roots.

The interactions did not appear to show any effects of importance.

Oxygen diffusion rate (ODR)
around the groove profiles:

Table 21 shows the ODR regimes around the groove profiles, as a function of opener types and the contrasting residue conditions, together with the interactions between these two parameters. The ODR measurements were taken on days 0, 5, 10, 15 and 20 (the final day). From the Table, there appeared to be no significant effects of opener types or contrasting surface residue conditions on ODR regimes around the groove profiles on any day during the experimental period.

Figure 27 shows the effects of opener types on changes in ODR regimes with time under the two crop residue conditions. It appears from all curves that between days 0 and 5 there was a rapid reduction in mean ODR values under both contrasting residue conditions, regardless of the geometry of the grooves. However, between days 5 and 20 the ODR regimes remained almost constant with no apparent difference between residue and no-residue conditions.

Earthworm populations:

The size of the experimental pot (160 x 160 x 200 mm) was small compared to the size of the tillage bins used in earlier experiments. Therefore, earthworm counts were made from the full pot rather than from discrete cores taken from around the groove profiles. Table 22 lists earthworm counts in the main and subtreatments. From the Table, it appeared that carbaryl had been very effective in eliminating the earthworms from the experimental site. The average numbers of earthworms per treatment were very small (less than one per pot) both under crop

Table 21: Effects of direct drilling opener types and contrasting crop residue conditions, on oxygen diffusion rate (ODR), in the absence of earthworms, under simulated rain conditions.

Days from sowing	Openers			Residue		Interactions				
	Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
	ODR ($g x 10^{-8}/cm^2/min$)									
0	34.9	33.9	35.6	34.6	34.9	NR	34.4	33.3	36.2	SED1=1.27
	Aa	Aa	Aa	Aa	Aa	R	35.5	34.5	34.9	SED2=1.28
5	8.3	8.1	8.6	8.2	8.5	NR	7.9	7.8	8.7	SED1=0.43
	Aa	Aa	Aa	Aa	Aa	R	8.6	8.3	8.5	SED2=0.26
10	7.9	7.8	8.2	7.9	8.1	NR	7.8	7.7	8.3	SED1=0.29
	Aa	Aa	Aa	Aa	Aa	R	8.0	7.9	8.1	SED1=0.30
15	7.9	7.7	8.3	7.9	8.0	NR	7.9	7.6	8.2	SED1=0.24
	Aa	Aa	Aa	Aa	Aa	R	7.8	7.7	8.2	SED2=0.19
20	8.3	8.0	8.3	8.2	8.3	NR	8.3	7.9	8.4	SED1=0.21
	Aa	Aa	Aa	Aa	Aa	R	8.4	8.1	8.3	SED2=0.22

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case $P<0.05$).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

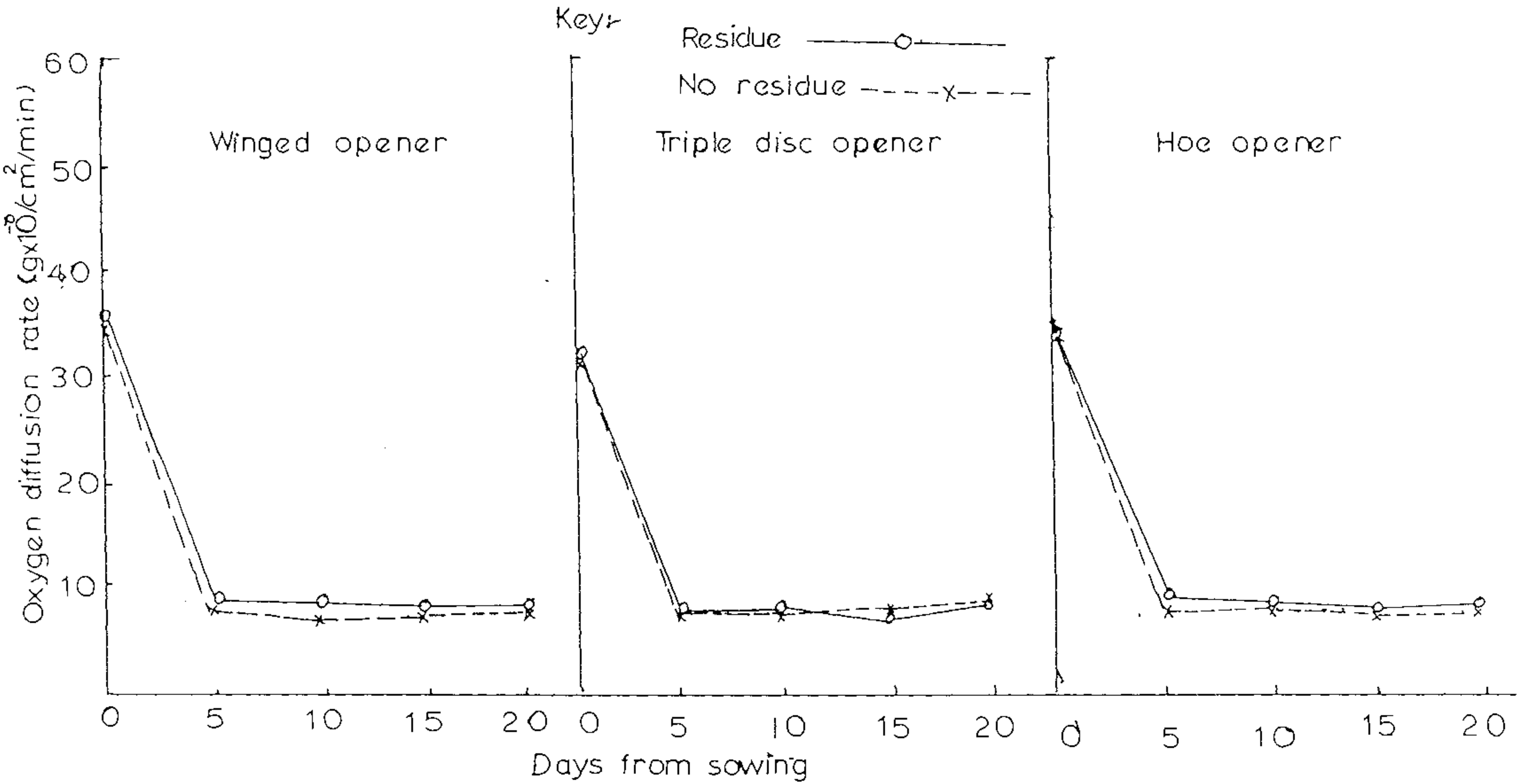


Figure 27: Effects of direct drilling opener types and contrasting crop residue conditions, on changes in oxygen diffusion rate(ODR) with time, in the absence of earthworms, under simulated rain conditions.

Table 22: Effects of direct drilling opener types and contrasting crop residue conditions, on earthworm populations around the groove profiles, under simulated rain conditions, in carbaryl treated pots.

Openers			Residue		Interactions				
Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
Populations per pot***									
1.0	1.0	1.7	1.1	1.3	NR	0.7	0.7	2.0	SED1=0.91
Aa	Aa	Aa	Aa	Aa	R	1.3	1.3	1.3	SED2=1.0

*NR = No surface residue present.
**R = Surface residue present.
*** = Pot volume approx 5.0 litres.
Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case $P<0.05$).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

Table 23: Effects of direct drilling opener types and contrasting crop residue conditions, on populations of earthworm species in the pots treated with carbaryl, under simulated rain conditions.

Earthworm species	Openers			Residue		Interactions				
	Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
	Populations per pot***									
A. longa	0.5	0.7	1.0	0.6	0.9	NR	0.0	0.3	1.3	SED1=0.71
	Aa	Aa	Aa	Aa	Aa	R	1.0	1.0	0.7	SED2=0.79
L. rubellus	0.3	0.2	0.5	0.4	0.2	NR	0.3	0.3	0.7	SED1=0.48
	Aa	Aa	Aa	Aa	Aa	R	0.3	0.0	0.3	SED2=0.27
A. caliginosa	0.3	0.0	0.2	0.1	0.2	NR	0.3	0.0	0.0	SED1=0.32
	Aa	Aa	Aa	Aa	Aa	R	0.3	0.0	0.3	SED2=0.39

*NR = No surface residue present.
**R = Surface residue present.
*** Pot volume approx 5.0 liters.
Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case, $P<0.05$).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

residue and no-residue conditions. It also appears from the Table that there were no significant effects of opener types or contrasting surface residue conditions on these small earthworm populations.

Table 23 shows the effects of carbaryl on the earthworm species (Allolobophora longa, Lumbricus rubellus, Allolobophora caliginosa). It appears from the Table that all the earthworm species were equally affected by the use of carbaryl and in all the pots there appeared to be very few unkilled earthworms, regardless of their species and the imposed opener/residue treatments.

Soil bulk density:

Table 24 shows the effects of opener types and contrasting surface residue conditions, on matrix soil bulk density, and the interactions between these two parameters. From the Table, it appears that opener types and contrasting surface residue conditions had no significant effects ($P<0.05$) on soil bulk densities around the grooves in the absence of earthworms. The soil bulk density under residue (1.47 g/cm^3) and no-residue conditions (1.47 g/cm^3) were also not significantly different. This was despite the fact that placement of seeds and electrodes had caused visible disturbance of the soil in the early stages of the experiment.

Soil moisture content:

Table 25 shows the effects of opener types and contrasting surface residue conditions, on matrix soil moisture content and the interactions between these two parameters. From the Table, it appears that opener types and contrasting surface residue conditions had no significant effects ($P<0.05$) on matrix soil moisture content (% d.b.) in the absence of earthworms.

Table 24: Effects of direct drilling opener types and contrasting crop residue conditions, on matrix soil density, in the absence of earthworms, under simulated rain conditions.

Openers			Residue		Interactions				
Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
Soil bulk density (g/cm^3)									
1.42	1.49	1.50	1.47	1.47	NR	1.40	1.50	1.51	SED1=0.078
Aa	Aa	Aa	Aa	Aa	R	1.43	1.49	1.49	SED2=0.079

Table 25: Effects of direct drilling opener types and contrasting crop residue conditions, on matrix soil moisture content, in the absence of earthworms, under simulated rain conditions.

Openers			Residue		Interactions				
Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
Soil moisture content (% d.b)									
40.2	40.0	41.2	40.1	40.8	NR	39.4	39.9	41.0	SED1=2.28
Aa	Aa	Aa	Aa	Aa	R	41.0	40.1	41.4	SED2=2.21

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote significant differences
upper case, P<0.01; lower case, P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

(b) Experiment 8; (In the presence of earthworms):

Seedling emergence:

Table 26 lists the effects of opener types and contrasting surface residue conditions, on seedling emergence, and the interactions between these two parameters. The Table shows that there were significant ($P<0.05$) effects of opener types on percentage seedling emergence when earthworms were present. The grooves of the triple disc opener showed significantly lower numbers of seedlings (60.0%) compared with the grooves of the winged (70.0%) and hoe (77.5%) openers, which were not significantly different.

The contrasting surface residue conditions also had a significant ($P<0.01$) effect on the mean percentage seedling emergence across all opener types. The crop residue conditions showed significantly higher numbers of seedlings (77.2%) compared to the no-residue conditions (61.1%).

There appeared to be strong interactions between opener types and crop residue conditions, with both residue and openers sharing about the same magnitude of influence. The hoe and winged openers promoted clearly the most emergence in residue conditions. Perhaps the hoe opener in no-residue was superior to the winged opener. The triple disc opener, on the other hand, was less sensitive to the presence or absence of residue.

Figure 28 shows the rates of seedling emergence under the two crop residue conditions. It appears that all treatments plateaued at about the same time (day 10). Those openers which eventually experienced the highest maximum emergence also displayed marginally steeper gradients during the first 5 days.

Ungerminated/dead seeds:

Table 26 also shows the effects of opener types and contrasting crop residue conditions, on ungerminated/dead seeds, and the interactions

Table 26: Effects of opener types and contrasting crop residue conditions, on the fate of direct drilled barley seeds, in the presence of earthworms, under simulated rain conditions.

Seed fate	Openers			Residue		Interactions				
	Winged	Triple disc	Hoe	* NR	** R	Openers/ Residue	Winged	Triple disc	Hoe	
Seedling emergence (%)	70.0 Aa	60.0 Ab	77.5 Aa	61.1 Bb	77.2 Aa	NR	53.3	63.3	66.7	SED1=5.77
						R	86.7	56.7	88.3	SED2=6.87
Ungerminated or dead seeds (%)	7.2 Bb	26.3 Aa	9.2 Bb	17.0 Aa	11.4 Ab	NR	11.7	29.0	13.3	SED1=3.13
						R	2.7	33.3	5.0	SED2=3.19
Germinated but unemerged seedlings (%)	22.8 Aa	13.7 Ab	13.3 Ab	21.9 Aa	11.3 Bb	NR	35.0	10.7	20.0	SED1=3.66
						R	10.7	16.7	6.7	SED2=4.11
Dry matter weight of roots (mg)	15.6 Bb	12.0 Bc	19.9 Aa	13.5 Bb	18.2 Aa	NR	12.0	12.9	15.5	SED1=1.2
						R	19.3	11.7	24.3	SED2=1.1

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote significant differences (upper case, P<0.01; lower case, P<0.05).
SED1=Standard error of difference witthin opener types.
SED2=Standard error of all other interactive differences.

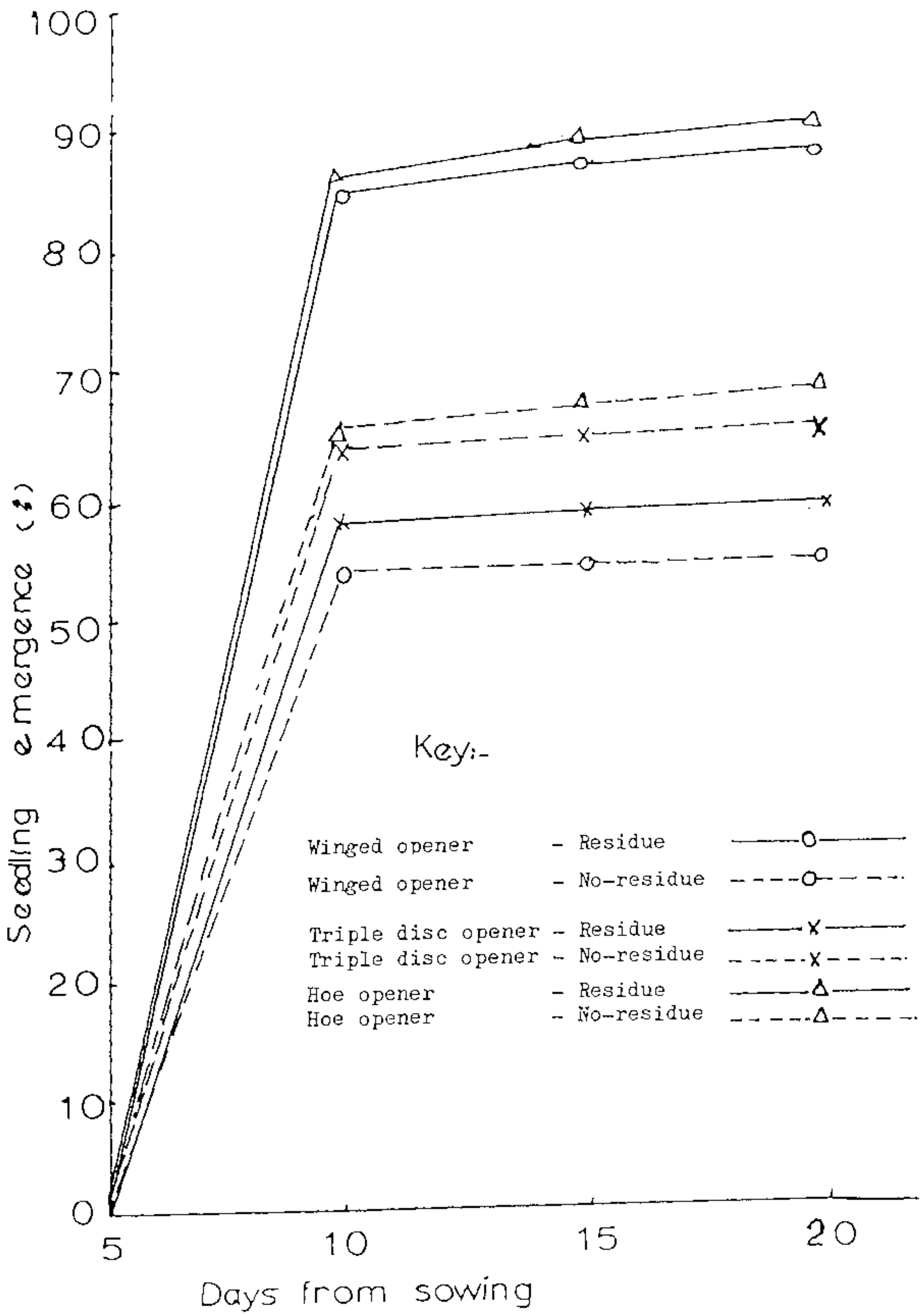


Figure 28: Effects of direct drilling opener types and contrasting crop residue conditions, on seedling emergence rates of barley, in the presence of earthworms, under simulated rain conditions.

between these two parameters. From the Table there appeared to be highly significant ($P<0.01$) effects of opener types on ungerminated/dead seeds. The grooves of the triple disc opener showed significantly higher numbers of ungerminated or dead seeds (26.3%) compared with the grooves of the winged (7.2%) and hoe openers (9.2%), which were not significantly different.

The contrasting surface residue conditions had a significant ($P<0.05$) effect on the mean of ungerminated/dead seeds in grooves of all opener types. The no-residue conditions (17.0%) showed significantly higher numbers of ungerminated/dead seeds compared with the residue conditions (11.4%).

The interactions between opener types and crop residue conditions appeared to favour the winged and hoe openers in residue. Again the triple disc opener appeared to be almost insensitive to the presence or absence of residue. The benefit which the winged and hoe openers gained by operating in residue was an approximately 3 fold reduction in ungerminated or dead seeds.

"Germinated but unemerged" seedlings:

Table 26 also shows the effects of opener types and contrasting crop residue conditions on "germinated but unemerged" seedlings. The grooves of the winged opener (22.8%) showed significantly ($P<0.05$) higher numbers of "germinated but unemerged" seedlings than the grooves of the triple disc (13.7%) and hoe (13.3%) openers, which were not significantly different.

The contrasting surface residue conditions had a highly significant ($P<0.01$) effect on the mean of "germinated but unemerged" seedlings across all opener types. The no-residue conditions appeared to have experienced higher counts of "germinated but unemerged" seedlings (21.9%) than surface residue conditions (11.3%).

The interactions between opener types and surface residue conditions showed that the grooves of the winged and hoe openers clearly benefitted from residue, while the grooves of the triple disc opener were unaffected. The highest counts of "germinated but unemerged" seedlings

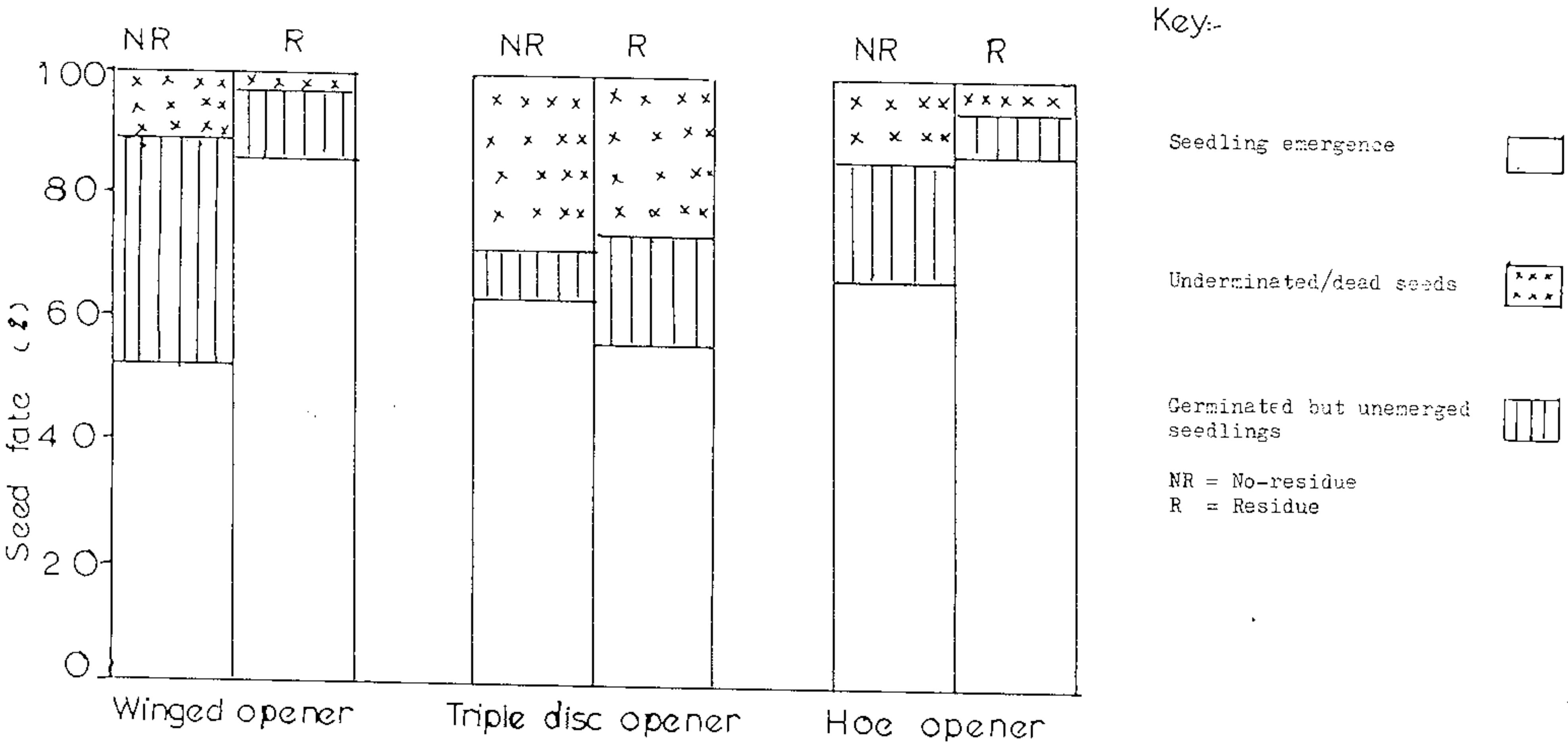


Figure 29: Effects of opener types and contrasting crop residue conditions on **cumulative** seed fate of direct drilled barley, in the presence of earthworms, under simulated rain conditions.

occurred with the winged opener in the absence of residue.

Summary of seed fate:

Figure 29 shows the collective seed fate data. The Figure shows that the lower counts of seedling emergence in the grooves of the triple disc opener reflected a relatively high number of ungerminated/dead seeds. By contrast the higher seedling emergence performances in the grooves of winged and hoe openers appeared to be accompanied by lower numbers of ungerminated/dead seeds. The Figure also illustrates the relatively high numbers of "germinated but unemerged" seedlings in the grooves of the winged opener in no-residue conditions.

Dry matter weight of roots:

Table 26 also shows the effects of opener types and contrasting crop residue conditions on the dry matter weights of plant roots, and the interactions between these two parameters. From the Table it appears that the grooves of the hoe opener recorded significantly ($P<0.05$) higher root weights per plant (19.9 mg) than the grooves of the winged opener (15.6 mg), which was itself significantly greater than the grooves of the triple disc opener (12.0 mg).

The contrasting surface residue conditions had a significant ($P<0.01$) effect on the mean root weights per plant across all opener types. The surface residue conditions showed significantly higher root weights per plant (18.2 mg) than the no-residue conditions (13.5 mg).

The interactions between opener types and surface residue conditions appeared again to illustrate the insensitivity of the triple disc opener to the presence or absence of residue, which was in contrast to the winged and hoe openers which responded favourably to residue conditions.

Oxygen diffusion rate (ODR)
around the groove profiles:

Oxygen diffusion rate measurements were taken on days 0, 5, 10, 15, and 20. Table 27 shows the effects on ODR regimes, of opener types and contrasting crop residue conditions, and the interactions between these

Table 27: Effects of direct drilling opener types and contrasting crop residue conditions, on oxygen diffusion rate (ODR), in the presence of earthworms, under simulated rain conditions.

Days from sowing	Openers			Residue		Interactions				
	Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
	ODR $(g \times 10^{-8}/cm^2/min)$									
0	47.7	44.9	45.4	46.7	45.3	NR	47.1	46.9	46.1	SED1=1.66
	Aa	Aa	Aa	Aa	Aa	R	48.4	42.9	44.7	SED2=1.67
5	18.2	15.1	16.3	15.5	16.7	NR	15.9	15.0	15.5	SED1=0.69
	Aa	Bb	Bb	Bb	Aa	R	20.4	15.1	14.7	SED2=0.81
10	15.5	14.1	15.9	13.7	16.5	NR	14.2	12.4	14.7	SED1=0.57
	Ab	Ab	Aa	Bb	Aa	R	16.8	15.8	17.1	SED2=0.63
15	15.2	12.6	14.8	12.3	16.2	NR	13.1	10.9	12.8	SED1=0.78
	Aa	Ab	Aa	Bb	Aa	R	17.3	14.4	16.8	SED2=0.68
20	14.8	13.5	14.9	13.1	15.7	NR	13.0	13.1	13.2	SED1=0.36
	Aa	Ab	Aa	Bb	Aa	R	16.5	13.8	16.6	SED2=0.29

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote significant differences (upper case, P<0.01; lower case P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

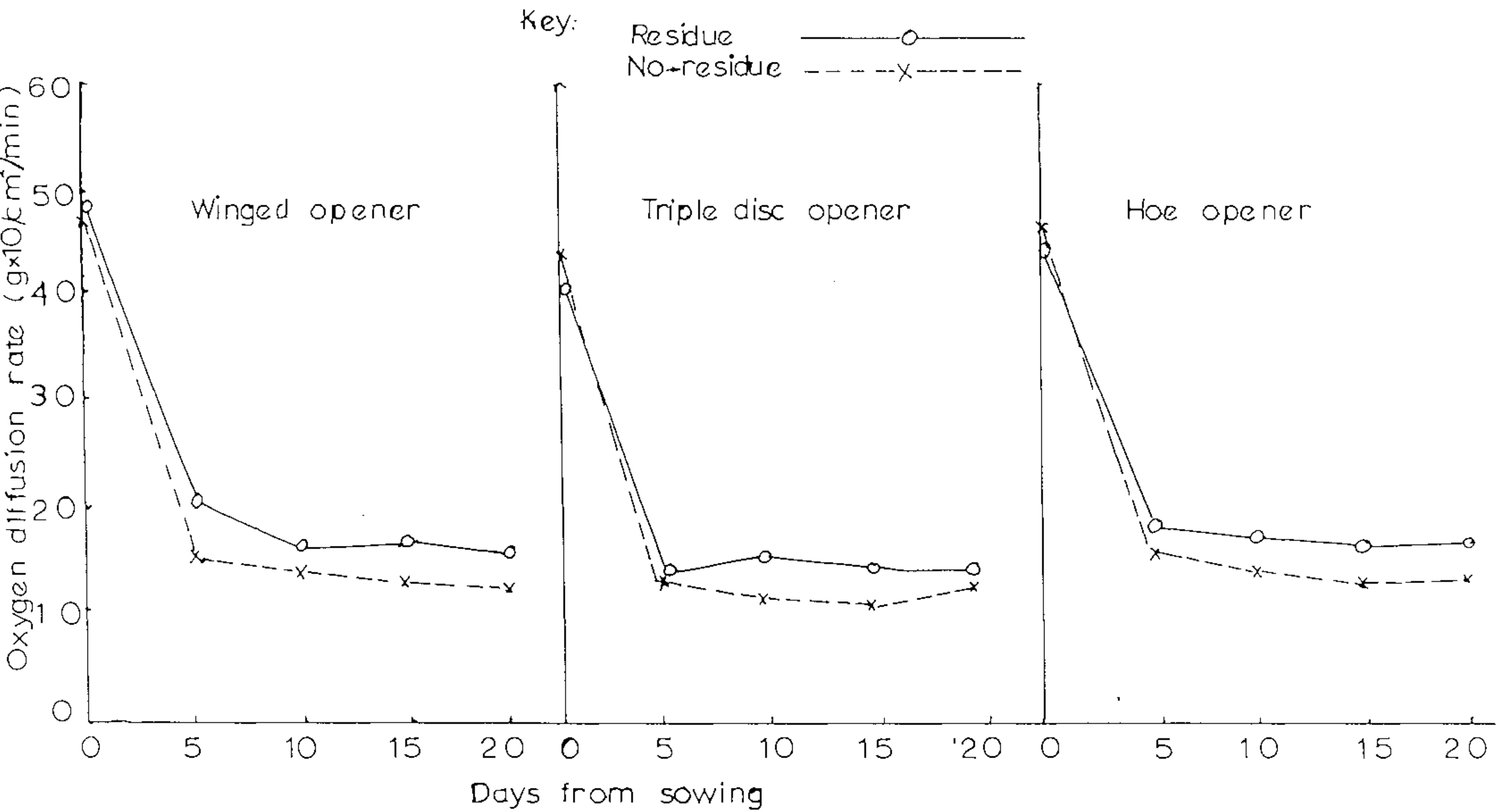


Figure 30: Effects of direct drilling opener types and contrasting crop residue conditions on changes in oxygen diffusion rate(ODR) with time, in the presence of earthworms, under simulated rain conditions.

two treatment factors. It appears from the Table that on day 0, there were no significant effects of opener types on ODR regimes. However, on days 5, 10, 15 and 20 the effects of opener types on ODR regimes were significant. On these days, a trend developed where the grooves of the triple disc opener showed significantly (P<0.05) lower ODR regimes compared to the grooves of the winged and hoe openers which were not significantly different.

The contrasting surface residue conditions had a significant (P<0.01) effect on the mean ODR across all opener types on days 5, 10, 15 and 20. On these days, the crop residue conditions showed consistently higher ODR regimes compared with no-residue conditions.

The interactions between opener types and surface residue conditions appeared to confirm the beneficial residue effects for each opener from day 10 onwards..

Figure 30 shows ODR regime changes for each opener type with time, under the contrasting residue conditions. It appears from all curves that the small pots in the experiment behaved in a similar manner to the larger tillage bins of the earlier experiments. Between days 0 and 5 there was a rapid reduction in mean ODR values under both contrasting residue conditions, regardless of the geometry of the grooves. Between days 5 and 20 the ODR regimes remained almost constant under residue conditions, but continued to decline slightly under no-residue conditions. The curves also illustrate that as the experiment advanced, the ODR values appeared to be consistently greater under residue conditions than under no-residue conditions.

Earthworm populations:

As with experiment 7, the numbers of earthworms were counted in the whole pots. Table 28 shows the effects of opener types and contrasting crop residue conditions, on earthworm populations, and the interactions between these two parameters. The Table shows no significant effects of opener types on earthworm populations. However, the contrasting surface residue conditions had a significant (P<0.05) effect on the mean of earthworm counts across all opener types. The crop residue conditions (26.4) showed significantly higher numbers of earthworms compared to the

Table 28: Effects of direct drilling opener types and contrasting crop residue conditions, on earthworm populations around the groove profiles, under simulated rain conditions.

Openers			Residue		Interactions				
Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
Populations per pot***									
22.3	21.2	21.5	16.9	26.4	NR	19.3	16.7	14.7	SED1=6.10
Aa	Aa	Aa	Bb	Aa	R	25.3	25.7	28.3	SED2=5.27

*NR = No surface residue present.
**R = Surface residue present.
*** Pot volume approx 5.0 litres.
Unlike letters in a row denote significant differences (upper case, P<0.01; lower case P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

Table 29: Effects of direct drilling opener types, and crop residue conditions, on polpulations of earthworm species, under simulated rain conditions.

Earthworm species	Openers			Residue		Interactions				
	Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
	Populations per pot***									
A. longa	3.8	4.0	6.0	4.6	6.0	NR	4.3	4.3	5.0	SED1=1.84
	Aa	Aa	Aa	Aa	Aa	R	3.3	3.7	7.0	SED2=1.50
L. rubellus	9.7	10.2	7.8	5.2	13.2	NR	6.0	5.0	4.7	SED1=3.16
	Aa	Aa	Aa	Bb	Aa	R	13.3	15.3	11.0	SED2=3.32
A. caliginosa	8.8	7.0	7.7	7.1	8.7	NR	9.0	7.3	5.0	SED1=2.55
	Aa	Aa	Aa	Aa	Aa	R	8.7	6.7	10.3	SED2=1.86

*NR = No surface residue present.
**R = Surface residue present.
*** Pot volume approx. 5.0 litres.
Unlike letters in a row denote significant differences (upper case, P<0.01; lower case, P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

no-residue conditions (16.9).

It was thought that the apparent insensitivity of earthworm numbers to groove shape in this experiment (which contrasted with the early bin experiment) may have been a reflection of the sampling procedure (of harvesting the entire pot compared with 120 mm dia x 100 mm discrete cores in the groove) as much as treatment effects. It seemed possible that any differences in populations which may have been very close to the grooves (as captured in a core of 1.13 litres volume) may have been over shadowed in these experiments by the general worm populations in the pots in general, which had volumes of approximately 5.0 litres each.

The interactions between opener types and surface residue conditions showed that the hoe opener benefitted most from the presence of crop residue.

Table 29 shows the total numbers of earthworm species active in the pots as a function of opener/residue treatments. The Table shows that only Lumbricus rubellus was more numerous in residue conditions compared with no-residue conditions (by a factor 2-3 fold). The interactions confirmed that this effect was consistent for each opener type. The numbers of Allolobophora longa and Allolobophora caliginosa were almost unchanged by the presence or absence of residue except that the numbers of Allolobophora caliginosa were twice as high in residue as in no-residue conditions with the hoe opener treatment. This may indicate that crop residue was more effective in increasing the earthworm populations (especially Lumbricus rubellus) than were opener types per se.

Soil bulk density:

Table 30 shows the effects of opener types and contrasting surface residue conditions, on matrix soil bulk density, and the interactions between these two parameters. From the Table it appears that opener types had no significant effects on soil bulk density, but the contrasting surface residue conditions had a significant ($P<0.01$) effect. The no-residue conditions (1.25 g/cm^3) showed a higher soil bulk density than the residue conditions (1.10 g/cm^3).

Table 30: Effects of direct drilling opener types and contrasting crop residue conditions, on matrix soil bulk density, in the presence of earthworms, under simulated rain conditions.

Openers			Residue		Interactions				
Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
Soil bulk density (g/cm^3)									
1.12	1.19	1.23	1.25	1.10	NR	1.19	1.27	1.29	SED1=0.061
Aa	Aa	Aa	Aa	Bb	R	1.06	1.07	1.17	SED2=0.049

Table 31: Effects of direct drilling opener types and contrasting crop residue conditions, on matrix soil moisture content, in the presence of earthworms, under simulated rain conditions.

Openers			Residue		Interactions				
Winged	Triple disc	Hoe	NR*	R**	Openers/ Residue	Winged	Triple disc	Hoe	
Soil moisture content (% d.b)									
31.3	29.9	32.7	31.0	31.6	NR	30.8	30.7	31.5	SED1=1.62
Aa	Aa	Aa	Aa	Aa	R	31.7	29.2	33.9	SED2=1.05

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case, $P<0.05$).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

The interactions between opener types and surface residue conditions, showed that the residue effect was consistent across each opener type.

Soil moisture content:

Table 31 lists the effects of opener types and contrasting surface residue conditions on matrix soil moisture content, and the interactions between these two parameters in the presence of earthworms. It appears from the Table that opener types and contrasting surface residue conditions had no significant effects on matrix soil moisture content.

3.4.4 Discussion of Experiments 7 and 8:

The two almost identical experiments showed contrasting results. In the absence of earthworms there were no significant effects of opener types on seedling emergence, ungerminated/dead seeds, "germinated but unemerged" seedlings or dry matter weights of plant roots. Similarly, the contrasting surface residue conditions had no significant effects on these parameters, with the exception that a significantly higher number of dead seeds was found under surface residue conditions than under no-residue conditions.

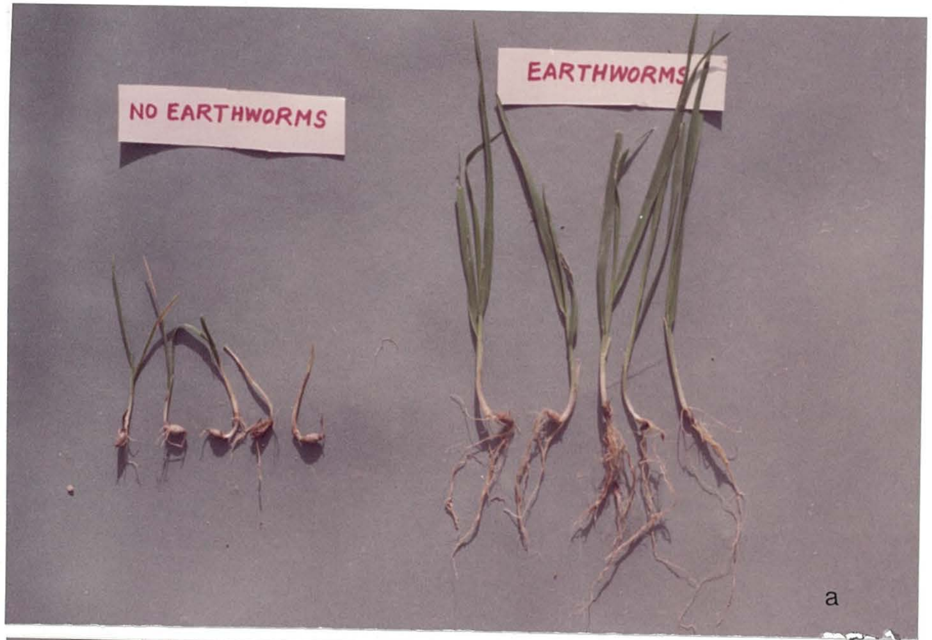
Figures 31 (a,b,c) show seedling root and shoot development in the absence and presence of earthworms. In the absence of earthworms (Fig. 31 (a and b)) root and shoot development appeared stunted compared with the situation when earthworms were present (Fig. 31 (a and c)). There also appeared to be a large number of ungerminated/dead seeds at the base of the groove in the absence of earthworms as illustrated in Fig. 31b. Figure 32 shows the effects of opener types on barley seedling emergence in the presence and absence of earthworms.

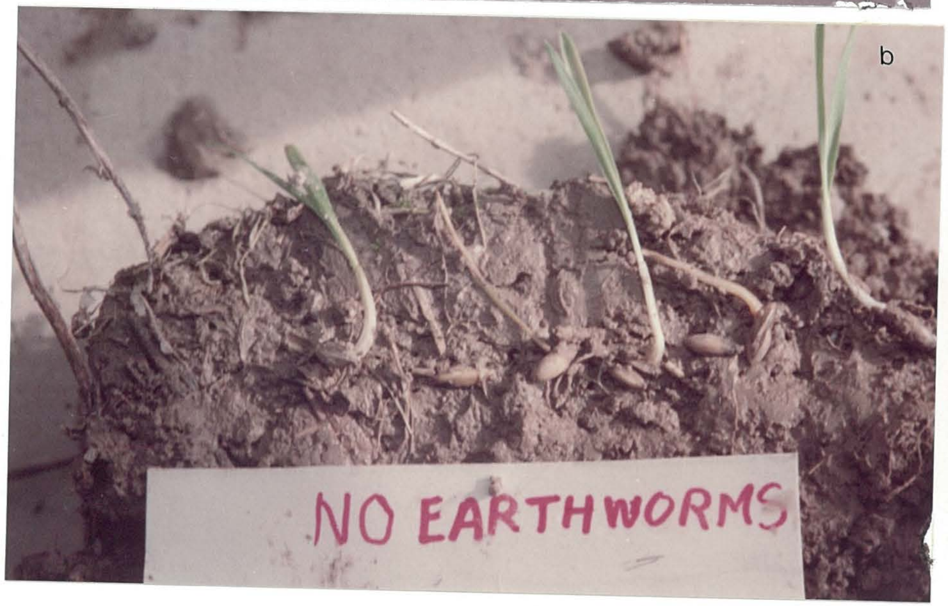
In the absence of earthworms the two major determinants, opener types and surface residue conditions, also had no significant effects on ODR regimes during the experimental period. The ODR values, in fact, were found to be much lower than the minimum requirements for barley (15 $\times 10^{-8}$ g/cm^2/min; Letey, 1964) in the grooves of all opener types and

Figure 31: Responses of barley seedlings to earthworms in a direct drilled groove.

(a). Note the shoot/root development in the absence and presence of earthworms.

(b) and (c). Note the glazed soil [illegible] appearance and ungerminated/dead seeds at the base of the direct drilled groove in the absence (b) of earthworms. This contrasts with the aerated appearance of soil in the presence of earthworms (c).





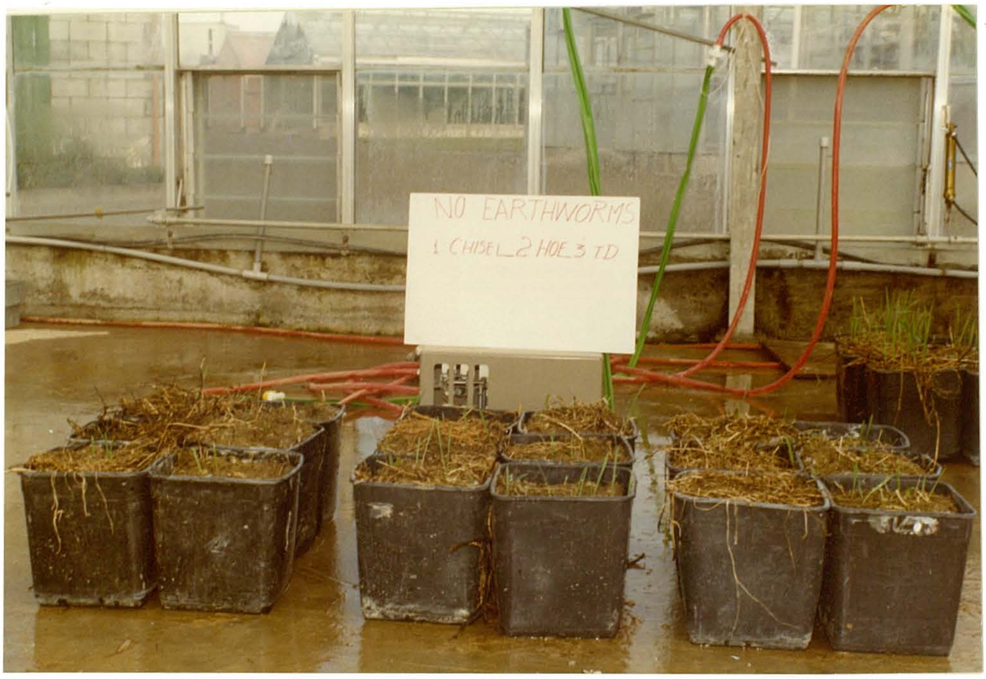


Figure 32: Effects of opener types and earthworms on barley seedlings, under simulated rain conditions.

Note the positive effects of earthworms on seedling emergence with all openers (above), compared with the poor emergence without earthworms (below).
Chisel = Winged opener; TD = Triple disc opener; Hoe = Hoe opener.

Fogure 33: The cast soil surface, with earthworms (above); and uncast soil surface without earthworms (below), under simulated rain conditions.

under both residue and no-residue conditions. They remained almost at the same level during the experimental period (Figure 27).

The soil bulk density and soil moisture measurements indicated that in the absence of earthworms, the mean soil bulk density under both surface residue conditions was high and there was no significant difference between treatments in this respect. Similarly, soil moisture contents were high under both residue and no-residue conditions and again were not significantly different between treatments. In general, the soil surface in the absence of earthworms had a plastic appearance and was at times slurried. Figure 33 illustrates the appearance of a soil surface in the absence of earthworms under wet soil conditions. The contrast between the appearance of the soil surfaces in the presence and absence of earthworms is clearly illustrated in the Figure. This was further illustrated by the absence of earthworm castings or holes on the soil surface. The adverse effects of soil compaction and high soil moisture content on ODR have been reported by several authors (Bertrand and Kohnke, 1957; Taylor, 1949; Raney, 1949). Others (Edwards, 1981; Edwards and Lofty, 1977; Springett, 1983) noted that earthworms turned over soil and helped in the formation of soil aggregates, while still other authors (Hopkin and Slater, 1949) claimed that soil with earthworms drained four to ten times faster than soil without earthworms. Clearly few of these desirable processes were occurring in this silt loam soil in the absence of earthworms.

By contrast the results obtained in the presence of earthworms were almost identical to those obtained earlier in the larger tillage bin experiments under simulated rain or temporary high water table conditions. It would be reasonable to conclude therefore, that the processes which affected the seed/soil environments around the profiles of the grooves created by the varying opener types in the presence of earthworms were similar to those already described in Experiments 2 and 3 (Section 3.2).

Earthworms, per se, appeared to be a very important factor in relation to seed and seedling responses, and all other treatment effects (seed sowing techniques and residue) had only indirect effects on seeds and seedlings, through their influences on earthworm numbers and activity.

It is also interesting to note that the different species of earthworms reacted differently to the imposed treatments. There were three earthworm species (Allolobophora longa, Lumbricus rubellus and Allolobophora caliginosa) present in the earthworm experiment. The presence and absence of crop residue had an effect on earthworm numbers, with 1.6 times more earthworms in the residue treatments than no-residue treatments. This difference was caused mainly by the difference in numbers of Lumbricus rubellus. The residue treatments had approximately 2.5 times more of this species than the no-residue treatments. There were much smaller differences in the numbers of Allolobophora caliginosa and Allolobophora longa between the two treatments. According to J. Springett (pers comm, 1983), "Lumbricus rubellus is a dung and litter feeding worm, highly pigmented dorsally and active at the soil surface. The two other species are soil dwelling and are less mobile. Allolobophora longa in particular has deep, relatively permanent burrows".

In residue treatments, Lumbricus rubellus made up 49% of the total worm population whereas it comprised only 30% of the population of no-residue treatments. The mobility and activity of Lumbricus rubellus could explain the observed differences in total worm populations which occurred within days of removing the crop residue from what were to become the "no-residue" plots. As Lumbricus rubellus is active at the soil surface, it was also thought that this species could have been making a notable contribution to the numbers of channels open to the atmosphere (J. Springett, pers. comm, 1983), which could explain some of the higher ODR readings in residue conditions. Such a source of aeration could have indirectly benefitted seed germination and seedling growth, provided that the crop residue was not pressed down in contact with the seeds, as apparently had occurred with the triple disc opener.

3.5 PHYTOTOXIC EFFECTS OF CROP RESIDUE IN THE PRESENCE OF EARTHWORMS (Experiment 9)

3.5.1 Objectives:

While much has been published about the phytotoxic effects of crop residue in-contact with seeds in wet cool (and at times anaerobic) conditions (Ellis et al, 1975; Lynch, 1977, 1978; Lynch et al, 1980), there is very little comparable information under wet warm conditions. Experiments (2, 3 and 8) indicated lower counts of seed germination and seedling emergence in the grooves of the triple disc opener in the presence of surface residue. This opener was seen to push the surface residue into the groove in such a way that it rested in contact with the seed. In these experiments, however, it was not clear whether the adverse effects on seed germination that were associated with crop residue, were a function of phytotoxicity alone or also a function of the geometry of the direct drilled grooves. An experiment was therefore conducted to study the effects of crop residue, pushed into the grooves created by different designs of openers, on seed and seedling performance under wet warm conditions.

3.5.2 Materials and methods:

The drilling operation was carried out in the field under surface residue conditions using triple disc and hoe openers. The winged opener was not used in this experiment, because it was not possible to push residue inside the groove created by this opener without disturbing the soil around the profile of this groove and thus modifying the groove geometry. Because the grooves created by the two test openers remained open at the soil surface, it was a simple matter to push the residue inside the grooves without disturbing the soil around the sides and bottom of the grooves.

There were three replicates of each of two treatments. These were residue "in-contact" (when residue was pushed inside the groove) and "not-in-contact" (where the residue was placed over the groove), with the two types of grooves ("V" and "U" shaped). Undisturbed soil blocks of 160 mm x 160 mm x 200 mm were cut with a spade and placed in plastic pots of the same size. These pots were shifted to a glasshouse and arranged in a split-plot design. Ten seeds were placed manually in each treatment in the same manner as previously described in Experiments 7 and 8. The residue was placed over the groove and pushed gently into them manually using forceps. Care was taken that in this process the geometry of the groove was not modified. The glasshouse climatic conditions involved simulated rain (20 mm a day) similar to those used in Experiments 7 and 8.

Seedling emergence, seed fate, root weights and earthworm populations were measured on the final day (day 21) of this experiment.

3.5.3 Results and discussion:

Seedling emergence:

Table 32 shows the effects of opener types and contrasting surface residue placements, on seedling emergence, and the interactions between these two parameters. From the Table, it appears that there were no significant effects of opener types on percentage seedling emergence.

The contrasting residue placements (residue "in-contact", and residue "not-in-contact") had a significant ($P<0.05$) effect on the mean of seedling emergence counts across both opener types. In this respect, residue "in-contact" showed significantly lower numbers of emerged seedlings (60.8%) than when the residue was "not-in-contact" with the seed (78.3%).

The interactions between opener types and contrasting residue placements showed that the grooves of the hoe opener benefitted from residue "not-in-contact".

Figure 34 shows the rate of seedling emergence, as affected by opener types under the two crop residue placements. It appears that all

Table 32: Effects of direct drilling opener types and contrasting residue placements, on the fate of direct drilled barley seeds, under simulated rain conditions.

Seed fate	Openers		Residue		Interactions			
	Triple disc	Hoe	* RC	** RNC	Openers/ Residue	Triple disc	Hoe	
Seedling emergence (%)	65.8	73.3	60.8	78.3	RC	60.0	61.7	SED1=7.73
	Aa	Aa	Ab	Aa	RNC	71.7	85.0	SED2=8.08
Ungerminated or dead seeds (%)	18.3	14.8	24.2	9.0	RC	25.0	23.3	SED1=3.97
	Aa	Aa	Aa	Bb	RNC	11.7	6.3	SED2=4.01
Germinated but unemerged seedlings (%)	15.8	11.8	15.0	12.7	RC	15.0	15.0	SED1=4.06
	Aa	Aa	Aa	Aa	RNC	16.7	8.7	SED2=4.56
Dry matter weight of roots (mg)	14.8	17.5	12.5	17.2	RC	12.5	13.0	SED1=1.54
	Aa	Aa	Bb	Aa	RNC	17.2	22.0	SED2=1.59

*RC = Residue "in-contact" with the seed.
**RNC = Residue "not-in-contact" with the seed.
Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case, $P<0.05$)
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

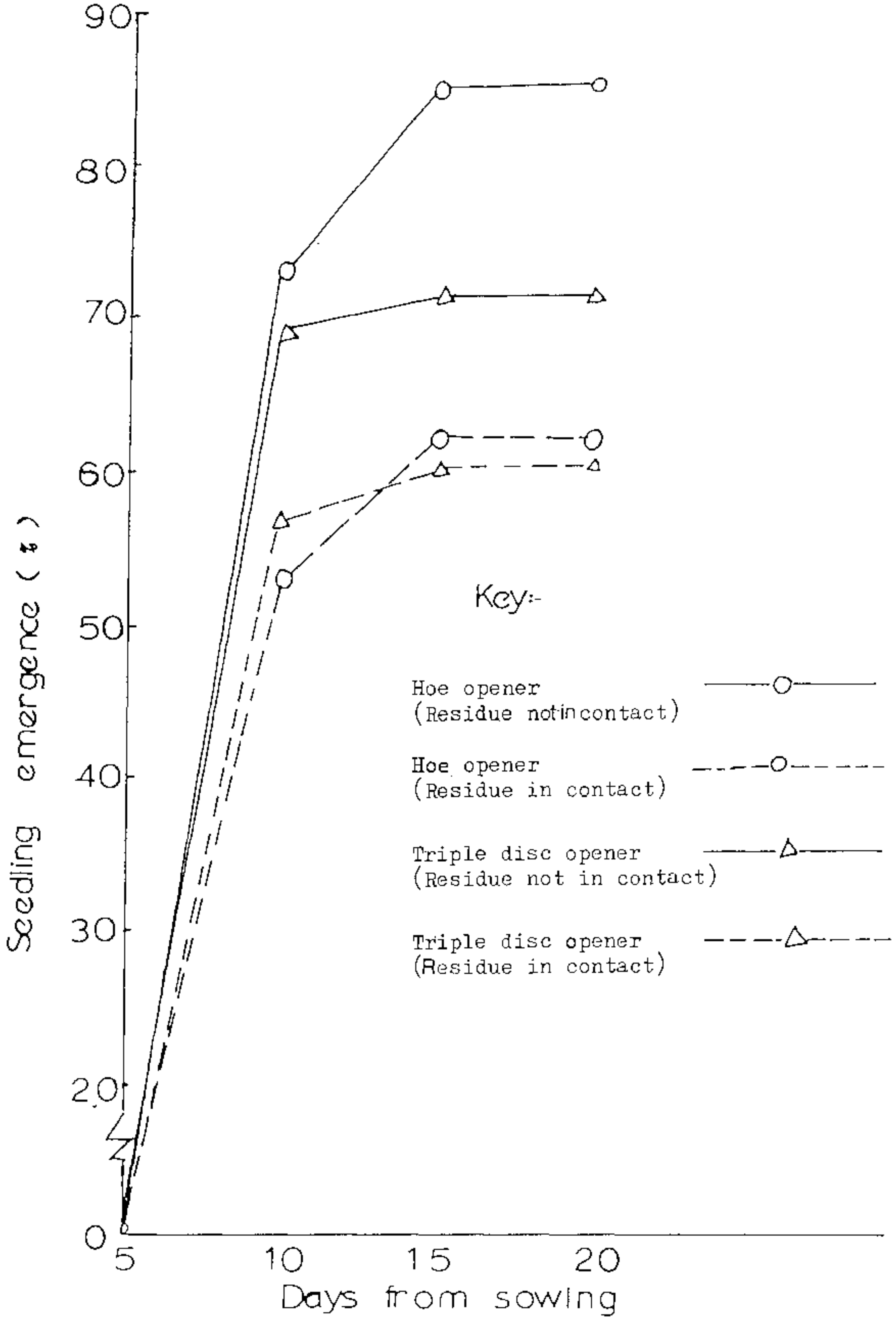


Figure 34: Effects of direct drilling opener types and position of crop residue on seedling emergence rate of barley, in the presence of earthworms, under simulated rain conditions.

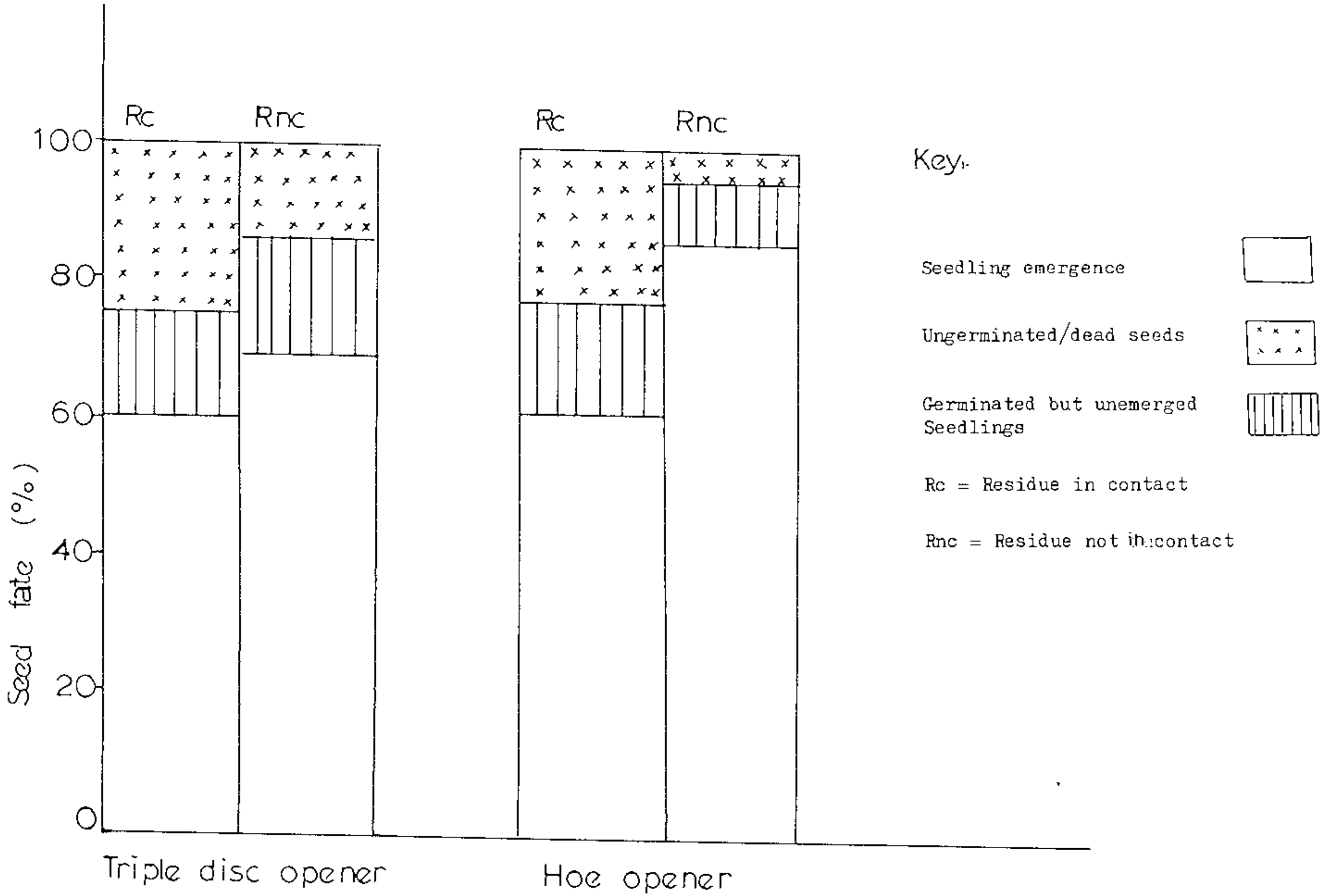


Figure 35: Effects of opener types and position of crop residue , on cumulative seed fate of direct drilled barley, in the presence of earthworms, under simulated rain conditions.

treatments plateaued at about the same time (day 15). As expected, those treatments which experienced the highest maximum emergence counts also showed a slightly more rapid rate of emergence between days 5 and 10. This was slightly slower than with the tillage bin experiments (2 and 3) which showed the most rapid seedling emergence gains during the first 5 days.

Ungerminated/dead seeds:

Table 32 also shows the effects of opener types and contrasting surface residue placements, on ungerminated/dead seeds, and the interactions between these two parameters. From the Table, there appeared to be no significant effects of opener types on the percentage of ungerminated/dead seeds. However, the contrasting surface residue placements had a highly significant ($P<0.01$) effect on the mean of ungerminated/dead seeds across both opener types. The "in-contact" residue conditions showed significantly higher numbers of ungerminated/dead seeds (24.2%) than the residue "not-in-contact" (9.0%).

The interactions between opener types and residue placements appeared to favour both openers where the residue was "not-in-contact" with the seed.

"Germinated but unemerged" seedlings:

Table 32 also shows the effects of opener types and contrasting surface residue placements, on "germinated but unemerged" seedlings, and the interactions between these two parameters. As with the other categories of seed fate, there appeared to be no significant effects of opener types on the numbers of "germinated but unemerged" seedlings. The contrasting surface residue placements also appeared to have had no significant effects on the mean of "germinated but unemerged" seedlings across both opener types.

Summary of seed fate:

The collective seed fate data are shown in Figure 35. From the Figure it is apparent that with the triple disc opener, in both residue positions, and the hoe opener with "in-contact" residue, the major problem was dead or ungerminated seeds. The hoe opener with residue "not-in-contact" appeared to have little problems and sustained a high seedling emergence. The Figure also shows that under these climatic conditions a reasonable level of barley emergence could be gained through ensuring that residue was "not-in-contact" with the seed, regardless of the geometry of the groove.

Dry matter weight of roots:

Table 32 lists the effects of opener types and contrasting residue placements, on dry matter weights of roots (mg/plant), and the interactions between these two parameters. It appears from the Table that there were no significant effects of opener types on root weights. However, the contrasting surface residue placements had a significant ($P<0.01$) effect on the mean dry matter weights of plant roots across both opener types. The residue "in-contact" showed a significantly lower root weight per plant (12.5 mg) than the residue "not-in-contact" (17.2 mg).

The interactions between residue placements and opener types showed a consistent trend for both opener types towards highest root weights with residue "not-in-contact". In this residue condition the hoe opener recorded a higher root weight than the triple disc opener.

Earthworm populations:

Table 33 shows the effect of opener types and contrasting crop residue placements, on earthworm populations, and the interactions between these two parameters. It appears from the Table that there were no significant effects of opener types and contrasting crop residue placements (residue "in-contact", residue "not-in-contact") on earthworm populations.

However, the interactions between opener types and contrasting residue placements favoured the hoe opener under residue "not-in-contact" compared to the triple disc opener under both residue positions, and the hoe opener under residue "in-contact" conditions. The grooves of the hoe opener experienced 1.5 times more earthworms than the grooves of the triple disc opener under residue "not-in-contact" conditions. The hoe opener also showed 1.6 times more earthworms under residue

Table 33: Effects of direct drilling opener types and contrasting residue placements, on earthworm populations, under simulated rain conditions.

Openers		Residue		Interactions			
Triple disc	Hoe	* RC	** RNC	Openers/ Residue	Triple disc	Hoe	
Populations per pot***							
24.2	28.0	23.0	29.2	RC	24.7	21.3	SED1=3.50
Aa	Aa	Aa	Aa	RNC	23.7	34.7	SED2=3.59

*RC = Residue "in-contact" with the seed.
**RNC = Residue "not-in-contact" with the seed.
*** Pot volume approx 5.0 litres.
Unlike letters in a row denote significant differences (upper case, P<0.01; lower case, P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

Table 34: Effects of direct drilling opener types and contrasting residue placements, on populations of earthworm species, under simulated rain conditions.

Earthworm species	Openers		Residue		Interactions			
	Triple disc	Hoe	* RC	** RNC	Openers/ Residue	Triple disc	Hoe	
	Populations per pot***							
A. longa	4.2	5.5	3.3	6.3	RC	4.0	2.7	SED1=1.12
	Aa	Aa	Ab	Aa	RNC	4.3	8.3	SED2=1.33
L. rubellus	8.2	11.7	9.3	10.5	RC	7.3	11.3	SED1=3.64
	Aa	Aa	Aa	Aa	RNC	9.0	12.0	SED2=2.41
A. caliginosa	10.8	10.8	9.2	12.5	RC`	11.3	7.0	SED1=2.20
	Aa	Aa	Aa	Aa	RNC	10.3	14.7	SED1=2.87

*RC = Residue "in-contact" with the seed.
**RNC = Residue "not-in-contact" with the seed.
*** Pot volume approx 5.0 litres.
Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case, $P<0.05$)
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

"not-in-contact" conditions than the grooves of the hoe opener in residue "in-contact" conditions. This might suggest that not only was soil compaction detrimental to earthworms with the triple disc opener, but an acid environment resulting from residue being pushed inside the groove might also have adversely affected earthworm populations.

Table 34 lists the three earthworm species in opener type/residue-placement treatments. The Table shows that with the triple disc opener grooves, each of the three earthworm species (Allolobophora longa, Lumbricus rubellus, Allolobophora caliginosa) were present in equal numbers, regardless of whether the residue was placed inside the groove or over the top of the groove. However, the pots with the hoe opener grooves, Allolobophora longa and Allolobophora caliginosa were twice as numerous where residue was placed over the top of the grooves than where it was placed inside it. In contrast to this the populations of Lumbricus rubellus were about equal with residue inside the groove or over the top of the groove, in the hoe opener grooves. Perhaps this indicates more tolerance of Lumbricus rubellus to fermenting residue decay (which would not be surprising as this species is a residue-feeder) than Allolobophora longa or Allolobophora caliginosa, which both appeared to reject decomposing residue which had otherwise been accessable in the non-compacted hoe opener grooves. Lumbricus rubellus was also more numerous in the hoe opener groove with "residue-in-contact" than in the triple disc opener groove with "residue-in-contact". Several authors had already reported that some earthworm species were sensitive to acid environment (Edwards and Lofty, 1972; Piearce, 1972). Therefore, these findings may support the results of these authors.

3.5.4 Discussion of Experiment 9:

The results of this experiment suggest that the geometry of the two contrasting grooves did not greatly affect seedling emergence, seed fate and root growth, so long as the residue was prevented from contacting the seeds in the grooves. Although no specific tests were conducted to identify the possible presence of toxins, it seems likely that phytotoxic effects of decomposing surface residue under these wet warm conditions may have occurred in a similar manner to those reported under wet cool conditions in England (Ellis et al, 1975; Lynch, 1977, 1978; Lynch et at, 1980).

3.5.5 Conclusions of Experiments 7, 8 and 9 :

From the results of Experiments 7, 8 and 9, it seems clear that under no-earthworm conditions neither the geometry of the grooves created by the three types of openers (winged, triple disc and hoe), nor the presence or absence of surface residue had any significant effects on seed germination or seedling growth. Overall, seed and seedling performance was poor in the absence of earthworms, partly because of low ODR regimes around all groove profiles.

On the other hand where earthworms were present under wet warm conditions, there were clear effects of opener types (favouring the winged and hoe designs) and surface residue (favouring the retention of residue on the groove surface).

It seemed reasonable, therefore, to investigate the effects of a wider range of opener types on seed germination and seedling growth in the presence and absence of earthworms and different surface residue under wet warm controlled climatic conditions.

3.6 DIRECT DRILLING SEED SOWING TECHNIQUES, EARTHWORMS, AND SURFACE RESIDUE IN A WET SOIL. (Experiments 10 and 11)

3.6.1 Intoduction:

Results of Experiments 7 and 8 in (Section 3.4) in the absence and presence of earthworms under contrasting surface residue conditions, had strongly suggested the importance of earthworm activity and its indirect effects on seed germination and seedling growth. In the earlier experiments three contrasting types of openers (winged, triple disc and hoe) were used.

The two experiments reported below were designed to test the performance of a wider range of opener types, together with surface broadcasting of seeds, in the presence and absence of earthworms and under contrasting surface residue conditions. Although a greater variation in the groove geometry was sought, it was decided also to resubmit the winged, triple disc and hoe designs for re-evaluation. This was for the following reasons:

In the earlier experiments the glasshouse temperature range (20-25 ^{o}C) was thought to be a little high for New Zealand conditions, and may have stimulated essential (and perhaps atypical) earthworm activity and ODR regimes around the groove profiles. Thus it was felt appropriate to test all opener types under a lower range of temperature (15-20 ^{o}C).

The experiments conducted in the absence (7) and presence (8) of earthworms had used small pots. It was considered possible that these may have unnaturally restricted the range of earthworm travel. Thus, it was felt desirable to study the effects of all opener types in the larger soil volumes of the tillage bins, in the presence and absence of earthworms. This had not been under-taken previously.

The "V" and "U" shaped grooves of the triple disc and hoe openers formed continuous narrow grooves at their bases, but were open at the soil surface. It was felt appropriate to compare these with the "groove" of the punch planter opener which formed a series of discontinuous narrow "U" shaped holes, also opened at the soil surface.

In earlier experiments, assessment of earthworm influence had been limited to counting the numbers of earthworms around the groove profiles. In the experiment described below, in addition to the numbers of earthworms, an assessment was to be made of the activity of the earthworms by observations of castings and holes.

Thus it seemed appropriate to include all possible direct drilling seed sowing techniques, even at the expense of repeating some of those tested earlier. In any case, because of the magnitude of the differences between earlier experiments, repetition of some aspects of the experiments seemed appropriate.

3.6.2 Materials and methods:

The experimental constraints of performing two experiments in the glasshouse with 12 tillage bins at the same time, have been discussed in Section 3.2. Therefore, two separate experiments under contrasting surface residue conditions (Experiment 10, in the absence of earthworms and Experiment 11, in the presence of earthworms) were conducted sequencially. In these experiments the glasshouse temperature was maintained at 15-20 ^{o}C (compared with the 20-25 ^{o}C in earlier experiments). Simulated rain conditions of 20 mm a day were created with a soak-hose in the same manner as used and described in earlier experiments. A sample of day/night temperature and relative humidity changes inside the glasshouse with a nominally controlled temperature range of 15-20 ^{o}C is shown in Appendix 3b.

(a) Selection of opener types:

As explained above, of the five opener types and one surface broadcasting technique used in these experiments, three of the openers (winged, triple disc and hoe) were used and described in Section 3.2. A description of the remaining two opener types and the surface broadcasting technique follows:

Power-till opener

A garden-type rotary hoe (Figure 36) was used to create a groove 100 mm wide, and to a depth of 40 mm. The machine pulverised the soil and partially mixed the surface residue into the loose soil of the groove. The resulting groove was typical of that produced by some powered direct drilling openers (Dunbar et al, 1979). The width of 100 mm was also similar to at least the machine reported by Dunbar et al (loc cit) and was considered appropriate as it represented a marked increase in the cross-sectional area of the disturbed zone, compared with all of the other opener types.

Punch planter opener

Although a prototype punch planter was available (R. Lal, pers.comm, 1983) but this was not used in the experiment, as there was no convenient way of decreasing the intra-row seed spacing and increasing depth to standardise with the other treatments. Instead a simple core sampler of 11 mm diameter was used to make cylindrical holes of 40 mm depth (Figure 37). In this way a total of 50 holes per plot were made in each of the contrasting surface residue conditions. In residue conditions, the holes were made with the residue in place but care was taken to avoid pushing residue down into the seed zone. It is important to note, however, that the design of R. Lal (loc cit) would be unlikely to avoid pushing some residue down into the seed zone in normal operation, as it employed more of a wedging action. Moreover, and for the same reason, the machine reported by R. Lal (loc cit) might have produced some soil compaction which was probably absent with the corer.

Figure 36: A garden rotary hoe assembly to create a power-till groove of 100 mm width. Note only one side of the assembly was used.

Figure 37: A core sampler (11 mm dia) used to make discrete holes (11 mm x 40 mm) to represent a punch planter opener.

Surface broadcasting

Seeds were manually placed in a row, both in no-residue and residue conditions in each plot. Care was taken in the residue condition to ensure that the seed rested on the soil surface, a situation likely to be more advantageous to the seeds than in general practice.

(b) Tillage bin technique:

Tillage bins were pulled into the residue covered soil and the contrasting surface residue conditions were created in the bins once they had been positioned, adopting the technique already explained in Section 3.2. To eliminate earthworm activity in the soil of the tillage bins, carbaryl was sprayed on the undisturbed soil blocks in bins at the rate of 2.0 kg/ha a.i. one week before the pre-drilling operation. The spraying technique was identical to that used in Section 3.3.

The predrilling operation of drawing the opener through the soil without sowing seed into the grooves, was performed in the field with the bins in place, after which the bins were shifted to their positions in the glasshouse. Fifty seeds in each treatment were manually sown using forceps. In the surface broadcasting operation, the fifty seeds were placed in a row of approximately 20 mm width.

(c) Measurements:

Measurements were made of seed fate, oxygen diffusion rate regimes (ODR), soil moisture contents, soil bulk density, earthworm populations, adopting the techniques used and discussed in Section 3.2. In those experiments, soil bulk density and soil moisture measurements were taken on the same day as the ODR measurements. In the present experiments, ODR measurements were taken on days 0, 7, 14 and 21, but soil bulk density and soil moisture measurements were taken only on day 21. This was to eliminate any possible effect on ODR during the experimental period from the holes left after taking soil samples for soil bulk density or soil moisture measurements.

The pattern of measurements to reflect ODR regimes in the vicinity of the grooves created by opener types, were identical to those patterns used beneath the row of the broadcasted seed. A similar pattern was adopted for all measurements of soil bulk density and soil moisture contents. No measurements of soil temperatures in the centre of the grooves were made because of the increased size of this experiment. The numbers of earthworms in the vicinity of the grooves were counted using a hand sorting technique from 120 mm diameter x 100 mm deep cores centered on the groove.

Observations of earthworm castings and holes were also made in the vicinity of the grooves. The area-index of earthworm activity used a 120 mm strip centered on the groove along the full length of the groove (1 m). For this purpose a quadrat of 3 mm diameter steel wire was placed parallel to and centered on the grooves. Each quadrat was divided into square sections of 120 mm x 120 mm area for ease and accuracy of sampling (Figure 38). Calculations of area-indices of earthworm activity were made as follows.

$$\text{Area index} = \frac{\text{Area covered by earthworm holes or castings } (m^2)}{0.12\ m^2}$$

(d) Experimental design:

The following comparative treatments were considered important.

Two levels of surface residue ("no-residue" and the residue which remained from the herbicide-killed pasture - "residue").

Six direct drilling seed sowing techniques (winged, triple disc, hoe, power-till and punch planter openers, and surface broadcasting).

Two earthworm levels (with and without earthworms).

Figure 38: A quardrat used for measuring area index of earthworm activity.

(Chisel = Winged opener)

(e) Constraints:

A number of limitations were imposed on the experimental design because of the facilities available. These included the availability of the tillage bins (12) and glasshouse facilities at any one time. The size of each tillage bin was considered to be an additional constraint. It was not feasible to have six seed sowing treatments in one tillage bin of 0.67 m width and 2 m length. Therefore, three direct drilling seed sowing techniques were used at 150 mm spacing in each of two tillage bins. These represented one block of the experiment. Thus with three blocks in one experiment, a total of six tillage bins at one time were used.

Because of those restrictions it was not possible to compare all treatments in one large experiment under controlled conditions. It was therefore, decided to divide the experimental programme into two separate experiments with three replicates in each. Experiment 10 was conducted in the absence of earthworms, while Experiment 11 was conducted with natural earthworm levels. The treatment comparisons to be made within each of these experiments were identical and involved six direct drilling seed sowing techniques and two contrasting surface residue conditions.

Experiment 10 was conducted in the absence of earthworms. Tillage bins were drilled in the field at a moisture content in the mid zone of the "available" range and then removed to the glasshouse where they were kept under a simulated rain conditions of intensity 5 mm per hour for 4 hours a day, for 21 days.

Experiment 11 was conducted in the presence of earthworms. Tillage bins were drilled in the field at a similar moisture content to Experiment 10 and then removed to the glasshouse where they were kept under identical simulated rain condititons of Experiment 10.

In this way each experiment consisted of 6 main treatments x 2 sub-treatments in a split-plot design with three replicates. For each experiment, 6 bins were pulled into the soil. Each soil bin was split into two residue levels by cutting and removing the residue from one half. Each bin was then treated with three randomly allocated direct drilling seed sowing techniques and was then extracted from the soil.

The pretreated bins were shifted to the glasshouse and rearranged in a split-plot design, blocked into 3 replicates. Fifty seeds were placed manually (using forceps) in the grooves of the opener types and surface broadcasting treatment. The bins remained in the glasshouse under simulated rain condition for 21 days.

3.6.3 Effects of direct drilling seed sowing techniques and surface residue in the absence of earthworms. (Experiment 10)

(a) Objectives:

The principal objective of this experiment was to determine the effects on seed and seedling performance, and soil physical conditions, of six techniques of seed sowing in an untilled seedbed, and contrasting surface residue conditions under simulated rain, in the absence of earthworms, in a saturated soil.

(b) Results and discussion:

Seedling emergence:

Table 35 shows the effects of direct drilling seed sowing techniques and contrasting surface residue conditions on seedling emergence and seed fate, together with the interactions between these two parameters, under wet soil conditions in the absence of earthworms. There were significant ($P<0.05$) differences in seedling emergence percentage, due to direct drilling seed sowing techniques. Surface broadcasting recorded clearly the highest seedling emergence count of 89.0%, followed by the grooves of the power-till opener (42.3%). The grooves of the hoe (23.3%) and winged (21.0%) openers came next with a further group of openers comprising the triple disc (17.0%) and punch planter (15.0%) showing less emergence than any other treatment except the winged design.

The contrasting surface residue conditions appeared to have no significant effects on seedling emergence percentage ($P<0.05$).

The interactions between direct drilling seed sowing techniques and contrasting surface residue showed only the grooves of the triple disc to

Table 35: Effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on seed fate of barley, in the absence of earthworms, under simulated rain conditions.

Seed fate	Seed sowing techniques						Residue		Interactions							
	Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broadcasting	NR*	R**	Seed sowing techniques/ Residue	Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broadcasting	
Seedling emergence (%)	21.0 cd	17.0 d	23.3 c	42.3 b	15.0 d	89.0 a	34.9 a	34.3 a	NR	22.0	18.7	22.7	41.3	16.0	88.7	SED1=1.53
									R	20.0	15.3	24.0	43.3	14.0	89.3	SED2=1.65
Ungerminated or dead seeds (%)	41.5 a	45.7 a	41.0 a	29.7 b	47.7 a	4.7 c	34.3 a	35.7 a	NR	44.7	40.0	39.3	29.3	47.7	5.0	SED1=3.14
									R	38.3	51.3	42.7	30.0	47.7	4.3	SED2=2.27
Germinated but unemerged seedlings (%)	37.5 a	37.7 a	35.0 ab	27.7 b	37.3 a	6.3 c	30.6 a	29.9 a	NR	33.3	42.0	36.7	28.7	36.3	6.3	SED1=3.07
									R	41.7	33.3	33.3	26.7	38.3	6.3	SED2=3.30
Root weight (mg)	3.7 d	7.1 d	9.0 c	14.6 a	5.5 e	11.6 b	9.1 a	9.2 a	NR	7.0	7.6	9.0	14.3	5.0	12.0	SED1=1.7
									R	7.6	6.6	9.0	15.0	6.0	11.3	SED2=2.2
Shoot weight (mg)	22.3 b	19.1 bc	20.3 b	29.1 a	15.1 c	22.1 b	21.8 a	20.9 a	NR	22.3	21.3	21.6	29.0	15.0	21.6	SED1=2.3
									R	22.3	17.0	19.0	29.3	15.3	22.6	SED2=1.9

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote significant differences (P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

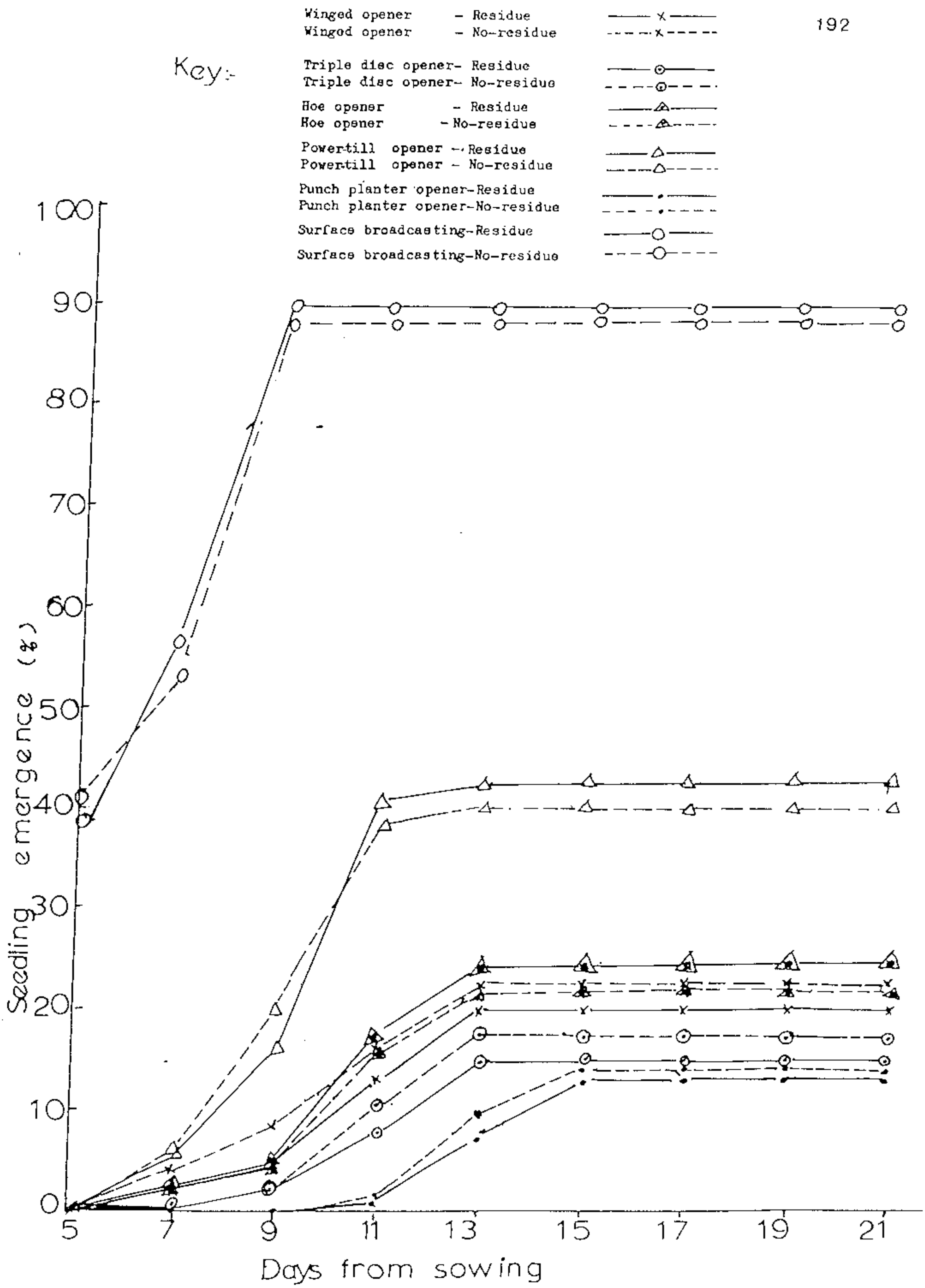


Figure 39: Effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on seedling emergence rates of barley, in the absence of earthworms, under simulated rain conditions

be sensitive to residue (and then as a negative response). All opener effects in the main treatment analyses were confirmed except that the winged opener was superior to the triple disc and punch planter openers in both residue and no-residue conditions.

Figure 39 shows the rate of seedling emergence, as affected by direct drilling seed sowing techniques under the two crop residue conditions in the absence of earthworms. The Figure illustrates that those treatments which experienced the highest maximum emergence counts also showed the most rapid rates of emergence, and plateaued at day 9.

Ungerminated/dead seeds:

Table 35 also shows the effects of direct drilling seed sowing techniques and contrasting surface residue conditions, on ungerminated/dead seeds, together with the interactions between these two parameters, in the absence of earthworms. From the Table, there appeared to be a significantly ($P<0.05$) larger number of ungerminated or dead seeds in the grooves created by the winged (41.5%), triple disc (45.7%), hoe (41.0%) and punch planter (47.7%) openers compared with the grooves of the power-till (29.7%), which was itself significantly higher than surface broadcasting (4.7%). The percentage ungerminated/dead seeds in the grooves of the former four openers were not significantly different.

The contrasting surface residue conditions had no significant effects on the numbers of ungerminated/dead seeds.

The interactions between direct drilling seed sowing techniques and surface residue conditions showed that both surface broadcasting and the next most favourable treatment (power-till) were unaffected by surface residue. All other opener treatments, except the punch planter opener responded to the presence or absence of residue, although the triple disc opener was disadvantaged by the presence of residue.

"Germinated but unemerged" seedlings:

Table 35 also shows the effects of direct drilling seed sowing techniques and contrasting surface residue conditions on the numbers of "germinated but unemerged" seedlings in a wet soil in the absence of earthworms. From the Table there appeared to be a significantly ($P<0.05$) higher number of "germinated but unemerged" seedlings with the grooves of the winged (37.5%), triple disc (37.7%), hoe (35.0%) and punch planter (37.3%) openers, compared with the grooves of the power-till opener (27.7%), which was itself significantly higher than surface broadcasting (6.3%).

The contrasting surface residue conditions had no significant effects on the percentages of "germinated but unemerged" seedlings.

The interactions between direct drilling seed sowing techniques and surface residue conditions showed that only the winged and triple disc openers were affected by the presence of residue. In the former case, a positive response resulted, while with the latter opener the response was negative.

Summary of seed fate:

The collective seed fate data are shown in Figure 40. From the Figure it is apparent that with the grooves of the triple disc and hoe openers under residue conditions; the winged opener under no-residue conditions; and the punch planter opener under both residue and no-residue conditions; the major problem was ungerminated/dead seeds. The grooves of the power-till opener showed about equal numbers of ungerminated/dead seeds and "germinated but unemerged" seedlings in both residue conditions, but overall lower numbers of both compared to all other seed sowing techniques except surface broadcasting. This probably reflects higher oxygen availability at the surface for the uncovered seeds in a continuously wet soil. In the case of the grooves of the power-till opener the greater zone of disturbed soil (100 mm wide strip) appears to have increased oxygen in the seed zone more than the more confined grooves of other openers. The seed and seedling performance of the grooves of the power-till opener was the next most favourable after the surface broadcasting treatment.

The Figure also shows that under these soil and climatic conditions a reasonable level of barley seed emergence could be gained through surface broadcasting or by the use of a power-till opener compared with the other three different openers and punch planting systems.

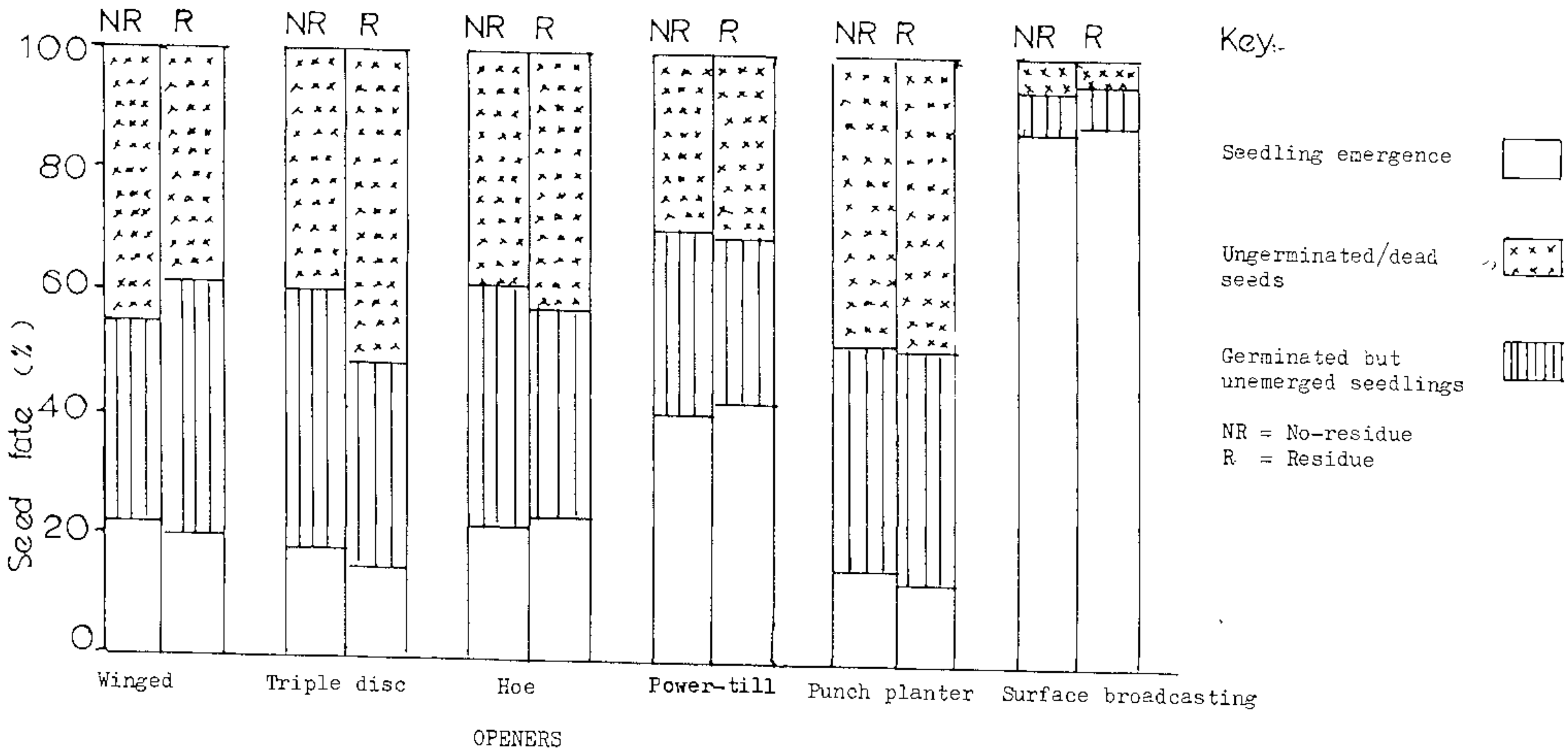


Figure 40: Effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on cumulative seed fate of barley, in the absence of earthworms, under simulated rain conditions.

Dry matter weight of roots:

Table 35 also shows the effects of seed sowing techniques and contrasting surface residue conditions, on dry matter weights of roots (mg/plant), and the interactions between these two parameters. The grooves of the power-till yielded significantly ($P<0.05$) heavier root weights (14.6 mg) than surface broadcasting (11.6 mg) which achieved significantly heavier root weights than the grooves of the hoe (9.0 mg) opener. This in turn yielded significantly heavier roots than the grooves of the winged (7.3 mg) and triple disc (7.1 mg) openers, which were followed by a significant reduction by the punch planter to 5.5 mg.

The contrasting surface residue conditions had no significant effects on root weight per plant.

The interactions between direct drilling seed sowing techniques and surface residue conditions showed that even in no-residue the grooves of the power-till opener produced heavier root weights than all other combinations of openers and residue, except surface broadcasting. In fact, all openers appeared to be almost insensitive to the presence or absence of surface residue. Of interest, was the fact that although surface broadcasting showed superior seedling emergence, its root weight was lower than the power-till treatment. Perhaps this reflected an effect of incomplete seed/soil contact, which may have reduced penetration of the radicle under surface broadcasting.

Dry matter weight of shoots:

Table 35 also shows the effects of direct drilling seed sowing techniques and contrasting surface residue conditions on shoot weights per plant, together with the interactions between these two parameters. It appears from the Table that there were significant ($P<0.05$) effects of direct drilling seed sowing techniques on dry matter weights of shoots (mg/plant). The seedlings from the grooves of the power-till opener showed significantly higher shoot dry weights of (29.1 mg) compared with the seedlings from the grooves of the winged (22.3 mg), triple disc (19.2 mg) and hoe (20.3 mg) openers, together with surface broadcasting technique (22.1 mg). Seedlings from the grooves of the punch planter (15.1 mg) showed a significantly lower shoot weight per plant than all other openers except the triple disc.

The contrasting surface residue conditions had no significant effect on shoot weight per plant.

The interactions between direct drilling seed sowing techniques and surface residue conditions confirmed the consistent superiority of the grooves of the power-till opener over other opener types and surface broadcasting, under both residue conditions.

Oxygen diffusion rate (ODR)
around the groove profiles:

Table 36 lists the effects of direct drilling seed sowing techniques and surface residue conditions on ODR values in the zone of soil around the grooves, together with the interactions between these two parameters. From the Table , there appeared to be a significant ($P<0.05$) effect of seed sowing techniques on day 0 and a restricted number of such differences on days 7, 14 and 21. On day 0, the grooves of the winged opener showed a significantly higher ODR regime (36.9×10^{-8} $g/cm^2/min$) than all other treatments except for the grooves of the power-till (36.3×10^{-8} $g/cm^2/min$) and hoe (35.1×10^{-8} $g/cm^2/min$) openers. This latter group was also not significantly different from the grooves of the triple disc opener, but the larger group showed a significantly higher ODR regime than that around the grooves of the punch planter opener (32.9×10^{-8} $g/cm^2/min$) and surface broadcasting (32.2×10^{-8} $g/cm^2/min$). However, on days 7, 14 and 21 the ODR regime in the vicinity of the grooves of the power-till was the only one which maintained significant superiority over the ODR regimes around the grooves of all other opener types and surface broadcasting.

The contrasting surface residue conditions had no significant effects on ODR regimes around the groove profiles on any of the measuring days of the experiment.

The interactions between direct drilling seed sowing techniques and crop residue conditions appeared only to confirm the main and sub-treatment effects.

Figure 41 shows the ODR regime changes with time, for each of the

Table 36 : Effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on oxygen diffusion rate (ODR), in the absence of earthworms, under simulated rain conditions.

Days from sowing	Seed sowing techniques						Residue		Interactions							
	winged	Triple disc	Hoe	Power-till	Punch planter	Surface broadcasting	NR*	R**	Seed sowing techniques/ Residue	Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broadcasting	
	ODR $(g x 10^{-8}/cm^{2}/min)$															
0	36.9 a	34.7 bc	35.1 ab	36.3 ab	32.9 cd	32.2 d	34.6 a	34.8 a	NR	35.9	34.1	35.2	36.8	33.4	31.5	SED1=1.39
									R	38.0	35.3	35.1	35.8	31.9	32.9	SED2=1.51
7	5.5 b	4.9 b	5.3 b	7.3 a	4.5 b	5.2 b	5.6 a	5.4 a	NR	5.6	5.3	5.3	7.4	4.3	5.4	SED1=0.48
									R	5.4	4.6	5.2	7.0	4.8	4.9	SED2=0.37
14	4.6 b	5.0 b	5.2 b	8.3 a	4.7 b	4.9 b	5.5 a	5.4 a	NR	4.4	5.4	5.0	8.5	4.7	4.7	SED1=0.36
									R	4.8	4.6	5.4	8.1	4.7	4.9	SED2=0.29
21	4.8 b	4.6 b	5.7 b	8.1 a	5.1 b	4.6 b	5.3 a	5.6 a	NR	4.6	4.5	5.3	8.3	4.9	4.4	SED1=0.55
									R	4.9	4.7	6.1	7.8	5.3	4.7	SED2=0.28

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote significant differences ($P<0.05$).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

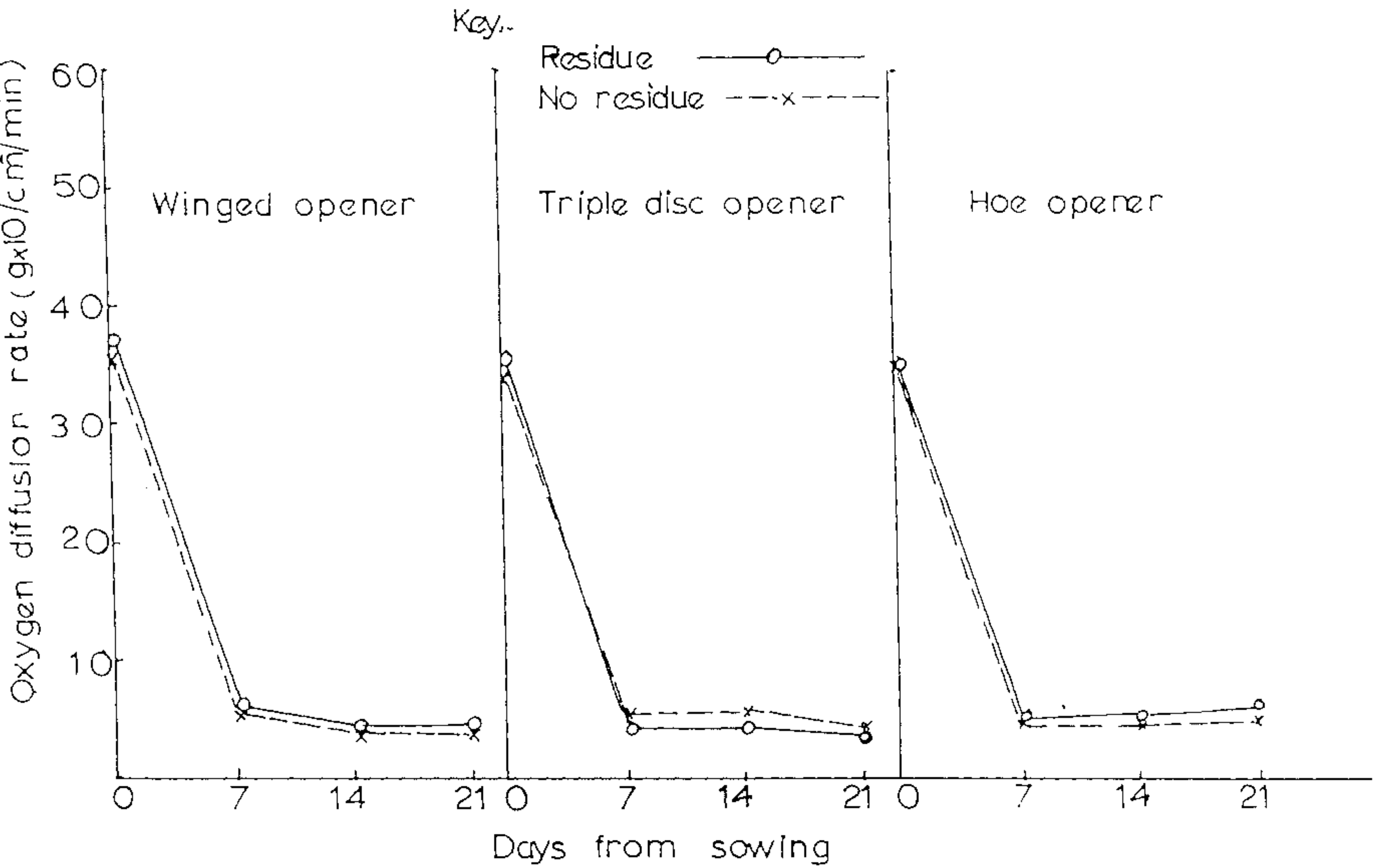


Figure 41: Effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on changes in oxygen diffusion rates (ODR) with time, in the absence of earthworms, under simulated rain conditions. (cont...

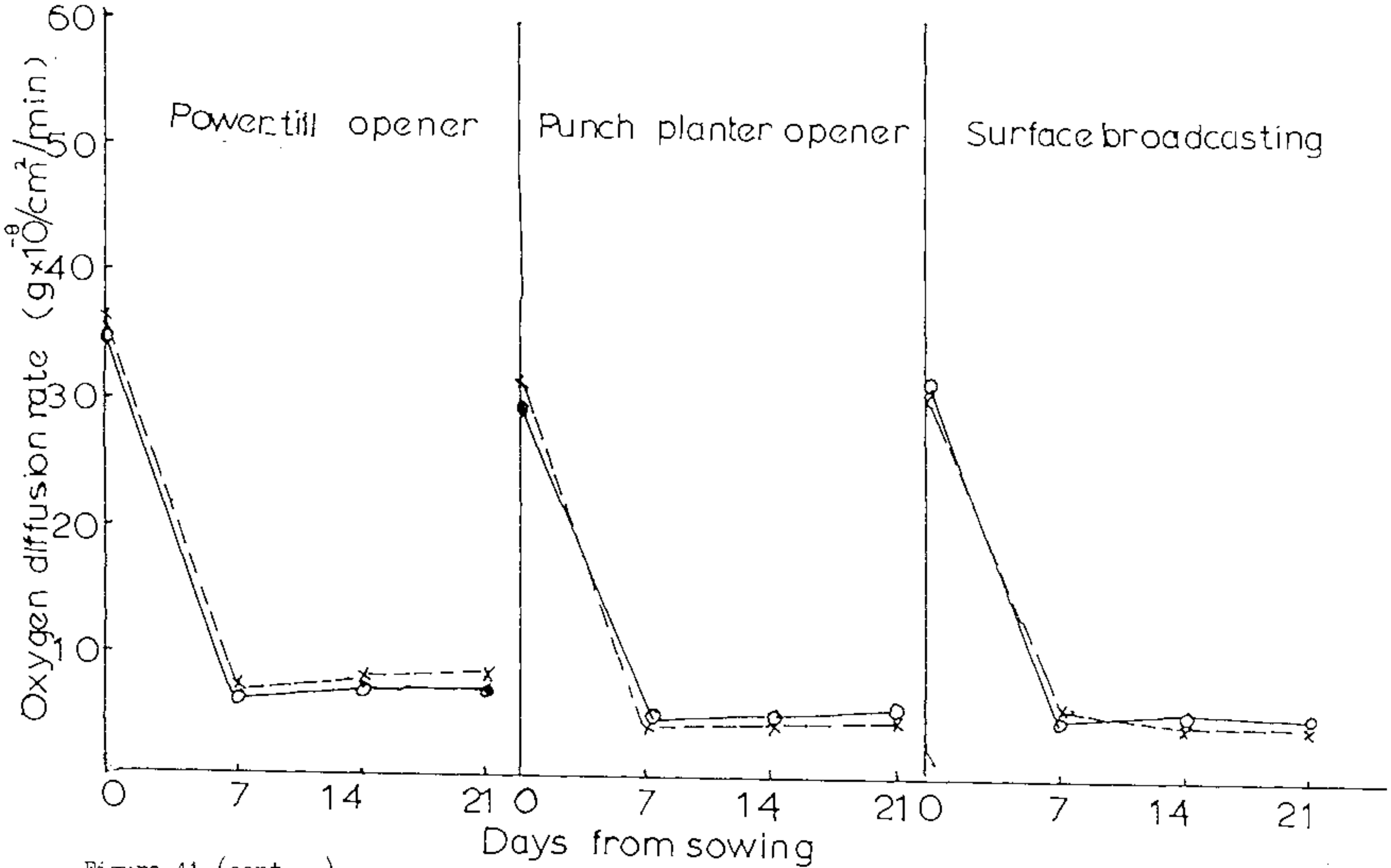


Figure 41 (cont...)

seed sowing techniques, under contrasting crop residue conditions. Between days 0 and 7, there was a rapid reduction in the mean ODR values under both contrasting residue conditions, regardless of the geometry of the grooves. However, between days 7 and 21 (the terminal day) ODR regimes remained almost constant under both residue conditions. The curves also illustrate that as the experiment advanced, ODR under residue and no-residue conditions appeared to be consistent. This trend seemed to be similar to that in experiment 7 (Section 3.4), in the absence of earthworms.

Earthworm populations around
the groove profiles:

Table 37 shows the effects of direct drilling seed sowing techniques and contrasting surface residue conditions, on earthworm populations, together with the interactions between these two parameters. From the Table, it appears that the use of carbaryl had caused mortality of almost all earthworms around the groove profiles, regardless of the geometry of the grooves. There were no significant effects of seed sowing techniques or contrasting surface residue conditions on earthworm populations around the groove profiles.

Soil bulk density around
the groove profiles:

Table 38 shows the effects of direct drilling seed sowing techniques and contrasting surface residue conditions, on soil bulk density around the groove profiles, together with the interactions between these two parameters. From the Table , there appeared to be a very small but significant ($P<0.05$) effect of direct drilling seed sowing techniques on soil bulk densities around the groove profiles. The grooves of the winged (1.34 g/cm^3), triple disc (1.34 g/cm^3), and power-till (1.34 g/cm^3) openers showed significantly higher bulk densities than the grooves of the punch planter (1.33 g/cm^3) and hoe (1.33 g/cm^3) openers and the surface broadcasting (1.33 g/cm^3) technique.

The contrasting surface residue conditions had no significant ($P<0.05$) effects on soil bulk densities around the groove profiles.

Table 37 : Effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on earthworm populations around the groove profiles, in the absence of earthworms (in carbaryl treated pots), under simulated rain conditions.

Seed sowing techniques						Residue		Interactions							
Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broad-casting	NR*	R**	Seed sowing techniques/ Residue	Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broad-casting	
Populations per core***															
0.8 a	0.5 a	1.2 a	2.0 a	1.5 a	0.7 a	1.7 a	0.5 a	NR	1.7	0.3	1.3	4.0	2.7	0.3	SED1=1.68
								R	0.0	0.7	1.0	0.0	0.3	1.0	SED2=1.73

*NR = No surface residue present.
**R = Surface residue present.
*** Core volume 1.13 litres.
Unlike letters in a row denote significant differences (P<0.05).
SED1=Standard error of difference within opener tyeps.
SED2=Standard error of all other interactive differences.

Table 38: Effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on soil bulk density and soil moisture content around the groove profiles, in the absence of earthworms, under simulated rain conditions.

	Seed sowing techniques						Residue		Interactions							
	Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broad-casting	NR*	R**	Seed sowing techniques/ Residue	Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broad-casting	
soil bulk density (g/cm^3)	1.34 a	1.34 a	1.33 b	1.34 a	1.33 b	1.33 b	1.33 a	1.34 a	NR	1.34	1.33	1.33	1.34	1.34	1.32	SED1=0.005
									R	1.33	1.35	1.34	1.34	1.33	1.34	SED2=0.006
Soil moisture content (% d.b)	38.4 d	39.6 a	38.9 bc	39.1 ab	38.6 cd	38.2 d	38.7 a	38.9 a	NR	37.6	39.6	38.9	39.5	39.5	37.9	SED1=0.339
									R	39.2	39.5	39.0	38.7	38.6	38.5	SED2=0.383

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote significant differences (P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

The interactions between direct drilling seed sowing techniques and surface residue conditions did not show any consistent trends. All values however (range 1.33-1.34 g/cm^3) were reasonably high in relation to favourable root growth conditions (1.32 g/cm^3), as reported by Mai (1978).

Soil moisture content around
the groove profiles:

Table 38 also lists the effects on soil moisture contents around the groove profiles of direct drilling seed sowing techniques and contrasting surface residue conditions, together with the interactions between these two parameters. The Table shows that there were small but significant ($P<0.05$) effects of direct drilling seed sowing techniques on percentage soil moisture contents (d.b) around the groove profiles. The grooves of the triple disc (39.6%) opener were slightly, but significantly, wetter than all other grooves except that of the power-till opener (39.1%). The next largest group of grooves were those of the power-till and hoe (38.9%) openers. This was followed by a group containing the grooves of the hoe and punch planter (38.6%) openers, which were themselves followed by a group of the punch planter and winged opener together with the surface broadcasting technique (38.2%). There were no significant differences between the grooves of the triple disc and power-till openers; nor between the grooves of hoe and power-till openers.

The contrasting surface residue conditions showed no significant effects on soil moisture content.

The interactions showed that while the winged opener gained soil moisture from the presence of residue, the power-till and punch planter openers lost soil moisture under the same conditions.

3.6.4 Effects of direct drilling seed sowing techniques and surface residue in the presence of earthworms (Experiment 11)

(a) Objectives:

The principal objective of this experiment was to determine the effects on seed and seedling performance and soil physical conditions of six techniques of seed sowing in an untilled seedbed, and contrasting surface residue conditions under simulated rain, in the presence of earthworms in a saturated soil.

In this experiment, the six direct drilling seed sowing techniques used were again the winged, triple disc, hoe, power-till and punch planter openers, and surface broadcasting. All other conditions during the experimental period were identical to Experiment 10.

(b) Results and Discussion:

Seedling emergence:

Table 39 shows the effects of direct drilling seed sowing techniques and contrasting surface residue conditions on percentage seedling emergence, and the interactions between these two parameters, in the presence of earthworms. There were significant ($P<0.05$) differences in percentage seedling emergence, due to opener types. The surface broadcasting showed a significantly higher percentage of seedling emergence (85.3%) than all other treatments. The power-till (62.3%) and winged (61.7%) openers were the next highest group, followed by a group containing the winged and hoe (52.3%) openers, which was itself followed by a group comprising the triple disc (21.0%) and punch planter (16.0%) openers.

The contrasting surface residue conditions had a significant ($P<0.05$) effect on the mean of seedling emergence across all opener types. The presence of surface residue showed a significantly higher

Table 39: Effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on seed fate of barley, in the presence of earthworms, under simulated rain conditions.

Seed fate	Seed sowing techniques: winged	Triple disc	Hoe	Power-till	Punch planter	Surface broad-casting	Residue: NR*	R**	Seed sowing techniques/ Residue	Interactions: Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broad-casting	
Seedling emergence (%)	61.7 bc	21.0 d	52.3 c	62.3 b	16.0 d	85.3 a	46.0 b	53.6 a	NR	48.0	24.7	40.0	62.0	14.7	86.7	SED1=6.15
									R	75.3	17.3	64.7	62.7	17.3	84.0	SED2=7.16
Ungerminated or dead seeds (%)	16.7 b	45.3 a	21.0 b	15.3 b	43.7 a	5.8 c	26.4 a	22.8 b	NR	20.3	42.0	26.7	16.7	46.7	6.3	SED1=4.62
									R	13.0	48.7	15.3	14.0	40.7	5.3	SED2=4.06
Germinated but unemerged seedlings (%)	21.7 c	33.7 b	26.7 c	22.3 c	40.3 a	8.0 d	27.6 a	23.6 b	NR	31.7	33.3	33.3	21.3	38.7	7.0	SED1=4.76
									R	11.7	34.0	20.0	23.3	42.0	10.7	SED2=5.45
Root weight (mg)	13.3 b	8.5 c	13.5 b	21.5 a	8.5 c	12.8 b	11.4 b	14.6 a	NR	11.0	9.6	12.3	18.3	6.3	11.0	SED1=1.6
									R	15.6	7.3	14.6	24.6	10.6	14.6	SED2=1.2
Shoot weight (mg)	33.0 b	20.5 d	29.1 c	45.5 a	24.0 c	27.1 c	28.1 b	31.6 a	NR	31.3	22.3	26.0	41.6	22.6	24.6	SED1=2.3
									R	34.6	18.6	32.3	49.3	25.3	29.6	SED2=2.1

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote significant differences (P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

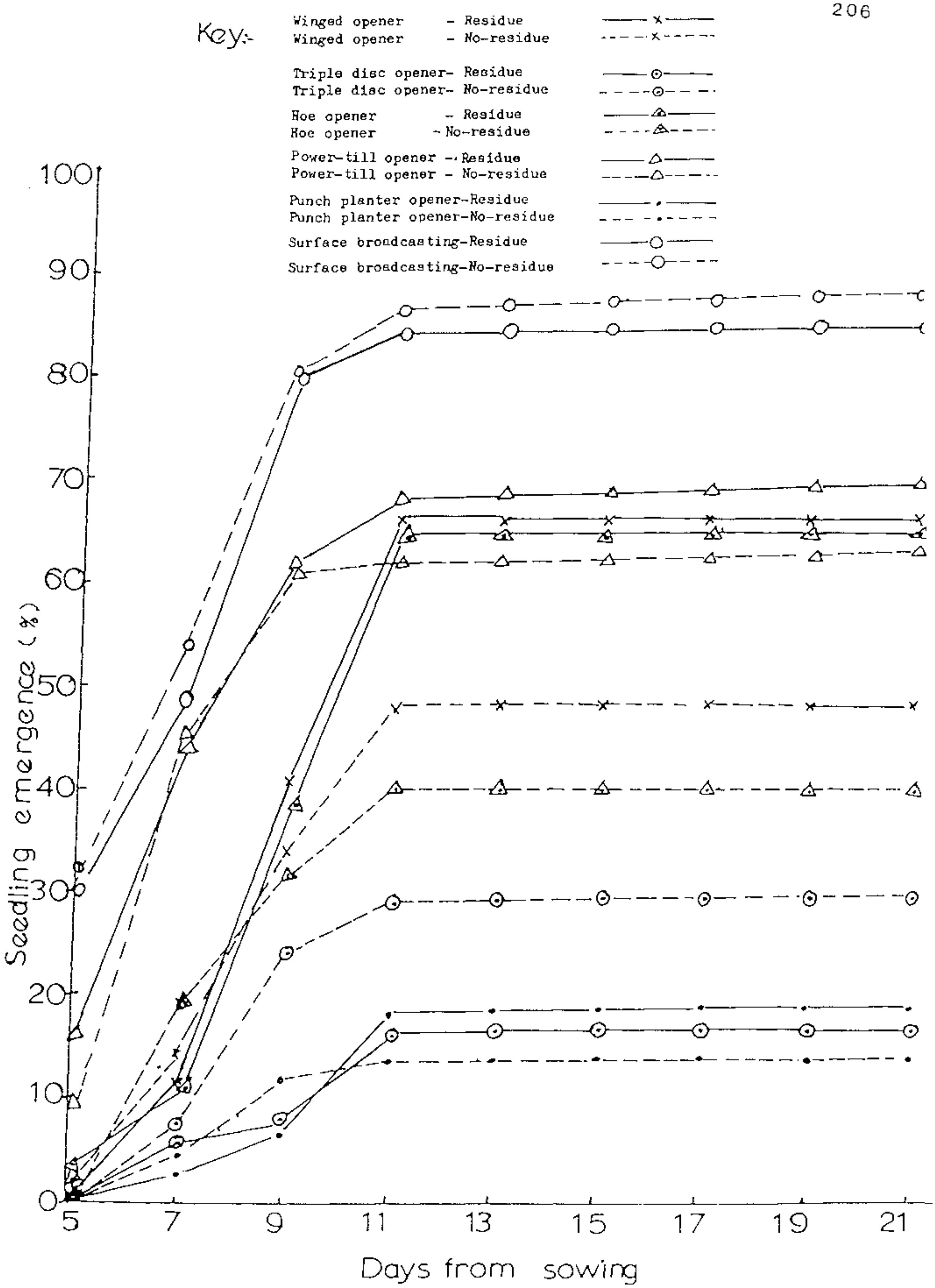


Figure 42: Effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on seedling emergence rates of barley, in the presence of earthworms, under simulated rain conditions.

number of emerged seedlings (53.6%) than where the surface residue was absent (46.0%).

There appeared to be strong interactions between direct drilling seed sowing techniques and surface residue conditions. The surface broadcasting, with and without surface residue, was superior to other openers and residue treatments, except the winged opener in residue. The latter opener was also similar to the hoe opener in residue and power-till opener with and without residue. Only the winged and the hoe openers in residue, and the power-till opener both with and without residue, promoted more than 50% seedling emergence. Under residue conditions the performance of the triple disc and punch planter openers, appeared to be very similar.

Figure 42 shows the rate of seedling emergence as affected by direct drilling seed sowing techniques in the two surface residue conditions. It appears that those treatments which eventually promoted 50% or more seedling emergence experienced an emergence rate almost twice that of those which achieved less than 50% maximum seedling emergence. However, all treatments plateaued at about the same time (day 11).

Ungerminated/dead seeds:

Table 39 also shows the effects of direct drilling seed sowing techniques and contrasting crop residue condtions, on ungerminated/dead seeds, and the interactions between these two parameters. The Table shows that there was a significantly ($P<0.05$) larger number of ungerminated/dead seeds in the grooves of triple disc (45.3%) and punch planter (43.7%) openers, compared with the grooves of the winged (16.7%), hoe (21.0%) and power-till (15.3%) openers, which were themselves more numerous than the surface broadcasting (5.8%) treatment.

The contrasting surface residue conditions had a significant ($P<0.05$) effect on the percentage of ungerminated/dead seeds. The absence of surface residue (26.4%) resulted in significantly ($P<0.05$) more dead or ungerminated seeds than where surface residue had been present (22.8%).

The interactions appeared to confirm trends from earlier experiments that the presence of surface residue reduced the numbers of ungerminated/dead seeds in the winged and hoe openers. Lowest overall numbers of such seeds were recorded with surface broadcasting (with and without residue) and the winged opener with residue. The best performed true opener x residue combinations appeared to be the winged and hoe openers in residue and the power-till opener with or without residue. The triple disc and punch planter openers both with and without residue, resulted in the highest counts of ungerminated/dead seeds. Perhaps the high number of dead seeds with the punch planter was due to its very confined discontinuous "groove" which was observed to accumulate water, in which the seed might have remained for an extended period of time.

"Germinated but unemerged" seedlings:

Table 39 also shows the effects of direct drilling seed sowing techniques and contrasting surface residue conditions, on "germinated but unemerged" seedlings, and the interactions between these two parameters. From the Table it appears that there were significant ($P<0.05$) effects of opener types on the percentage of "germinated but unemerged" seedlings. The "grooves" of the punch planter sustained the highest counts (40.3%) followed by the grooves of the triple disc (33.7%) opener, which were significantly greater than the grooves of a group of openers containing the winged (21.7%), hoe (26.7%) and power-till (22.3%) openers. The lowest count of "germinated but unemerged" seedlings was with the surface broadcasting treatment (8.0%).

The contrasting surface residue conditions had a significant ($P<0.05$) effect on the counts of "germinated but unemerged" seedlings with the lower count being associated with the retention of residue on the soil surface.

The interactions between direct drilling seed sowing techniques and surface residue conditions appeared to favour surface broadcasting and the winged opener in residue. The punch planter and triple disc openers were the only treatments to show reasonably large numbers of "germinated but unemerged" seedlings in residue.

Summary of seed fate:

The collective seed fate data are shown in Figure 43. Collectively the six treatments seemed to group themselves roughly into 3 groups. The surface broadcasting gave a very good performance and appeared to be little affected by the presence or absence of surface residue. The winged, hoe and power-till openers all performed reasonably well in residue but suffered a little without residue (except the power-till which was unaffected, possibily because it mixed the residue with the soil). Finally, the triple disc and punch planter openers both performed poorly although residue did help the performance of the punch planter a little.

Dry matter weight of roots:

Table 39 also shows the effects of direct drilling seed sowing techniques and contrasting surface residue conditions, on dry matter weights of roots, and the interactions between these two parameters in the presence of earthworms. From the Table, it is apparent that there were significant ($P<0.05$) effects of direct drilling seed sowing techniques on the per plant dry matter weights of roots. Roots in the grooves of the power-till opener were significantly heavier (21.5 mg) than roots in the grooves of the winged (13.3 mg) and hoe (13.5 mg) openers, together with surface broadcasting (12.8 mg). These, in turn were significantly heavier than roots in the grooves of the triple disc (8.5 mg) and punch planter (8.5 mg) openers.

The contrasting surface residue conditions had a significant ($P<0.05$) effect on the dry matter weights of roots per plant. The surface residue conditions (14.6 mg) showed significantly heavier root weights per plant than the no-residue conditions (11.4 mg).

The interactions between direct drilling seed sowing techniques and surface residue conditions showed that all treatments increased root weights in the presence of surface residue except the triple disc opener which decreased root weights by approximately 20%. This together with the punch planter opener in no-residue, appeared to record the lowest root weights of all direct drilling seed sowing techniques. The power-till opener recorded the highest root weight readings in the

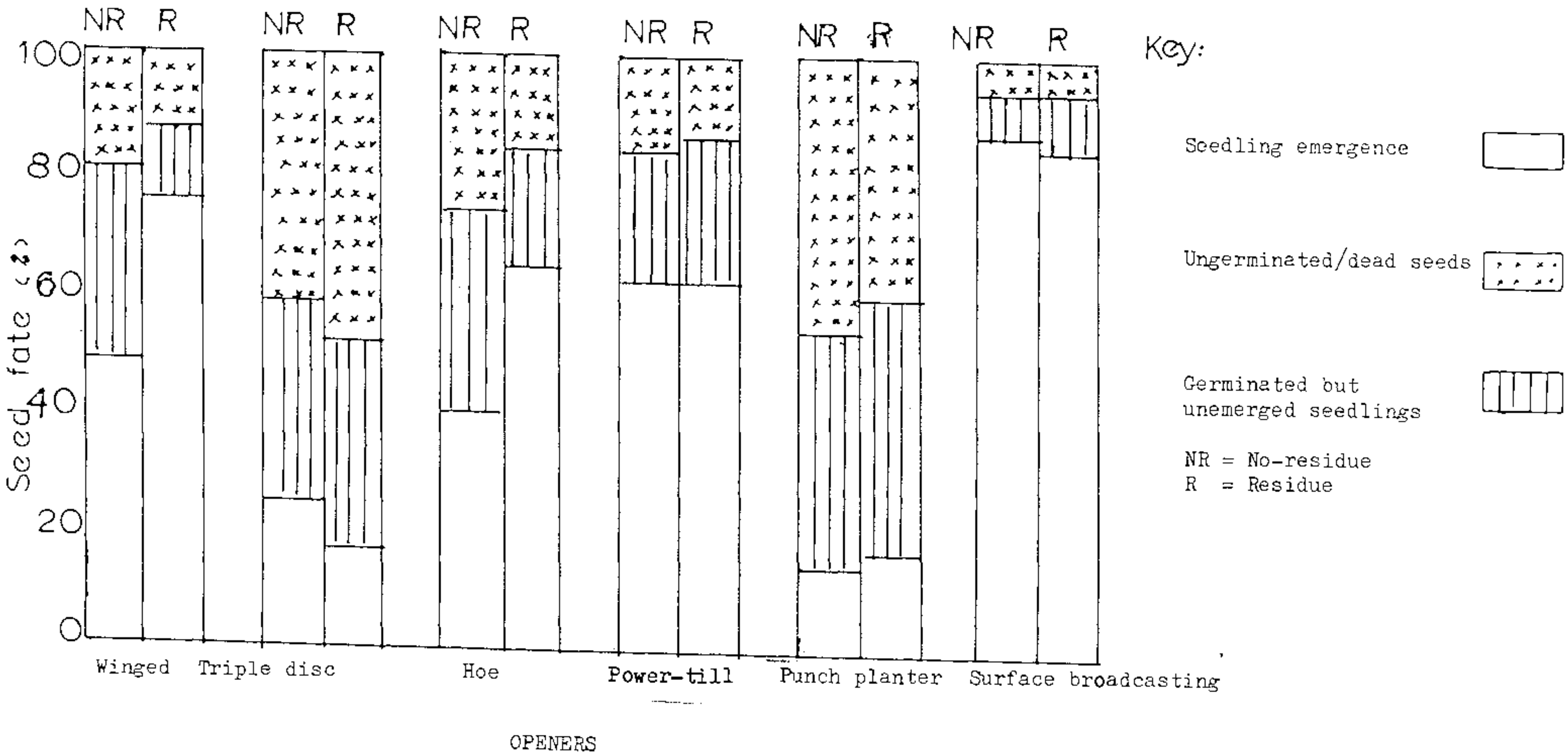


Figure 43: Effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on cumulative seed fate of barley, in the presence of earthworms, under simulated rain conditions.

presence of surface residue. Even without residue this opener recorded higher root weights than any other seed sowing technique.

Dry matter weights of shoots:

Table 39 also lists the effects of direct drilling seed sowing techniques and contrasting surface residue conditions, on dry matter weights of shoots and the interactions between these two parameters. From the Table, it appears that the shoot weight data were very similar to the root weight data. The grooves of the power-till opener had the heaviest shoots (44.5 mg), which were significantly ($P<0.05$) heavier than in the grooves of the winged opener (33.0 mg). These in turn were significantly heavier than the grooves of the hoe (29.1 mg) and punch planter (24.0 mg) openers and the surface broadcasting (27.1 mg) treatment, which were significantly heavier than in the grooves of the triple disc opener (20.5 mg).

The contrasting surface residue conditions had a significant ($P<0.05$) effect on shoot weights per plant. The presence of surface residue showed significantly higher shoot weights per plant (31.6 mg) than where surface residue was absent (28.1 mg).

The interactions between direct drilling seed sowing techniques and surface residue conditions indicated that the power-till and hoe openers and surface broadcasting benefitted from the presence of surface residue. The triple disc opener was disadvantaged by the presence of residue, and in fact, showed the lowest shoot weight per plant of all treatments. Again this might have reflected residue/seed contact. The shoot weights of the power-till opener, in residue, were higher than the next best treatments, which were the winged and hoe openers in residue.

Oxygen diffusion rate (ODR)
around the groove profiles:

Table 40 shows the effects of direct drilling seed sowing techniques and contrasting surface residue conditions, on ODR regimes around the grooves profiles, and the interactions between these two parameters on days 0, 7, 14 and 21. From the Table, there appeared to be no

Table 40: Effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on oxygen diffusion rate (ODR) around the groove profiles, in the presence of earthworms, under simulated rain conditions.

Days from sowing	Seed sowing techniques						Residue		Interactions							
	Winged	Triple disc	Hoe	Power-tili	Punch planter	Surface broad-casting	NR*	R**	Seed sowing techniques/ Residue	Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broad-casting	
			ODR $(g \times 10^{-8}/cm^2/mi)$													
0	49.7 a	49.8 a	49.9 a	49.6 a	47.8 a	48.3 a	48.9 a	49.5 a	NR	49.2	49.9	48.9	49.6	47.7	48.4	SED1=1.48
									R	50.2	49.8	50.8	49.6	48.0	48.3	SED2=1.54
7	18.2 b	16.8 c	17.8 b	21.0 a	17.1 c	16.8 c	17.3 b	18.6 a	NR	16.9	17.1	17.4	20.3	16.1	16.0	SED1=0.49
									R	19.4	16.4	18.1	21.7	18.0	17.7	SED2=0.59
14	14.4 b	12.7 c	14.3 b	17.8 a	14.1 b	14.4 b	12.5 b	16.7 a	NR	11.8	11.2	11.8	16.8	11.2	12.1	SED1=0.45
									R	16.9	14.3	16.8	18.9	17.0	16.6	SED2=0.46
21	15.3 a	12.9 b	14.9 a	14.7 a	13.4 b	13.2 b	12.2 b	15.9 a	NR	12.7	11.3	12.4	13.9	11.1	11.8	SED1=0.44
									R	17.9	14.4	17.5	15.4	15.7	14.7	SED2=0.38

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote significant differences ($P<0.05$).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

significant effects of direct drilling seed sowing techniques on ODR regimes on day 0. However, on days 7, 14 and 21, the effects of direct drilling seed sowing techniques were significant ($P<0.05$). On day 7, the ODR regimes around the grooves of the power-till opener were significantly higher (21.0×10^{-8} g/cm^2/min) than that around the grooves of the winged (18.2×10^{-8} g/cm^2/min) and hoe (17.8×10^{-8} g/cm^2/min) openers. These two were in turn significantly higher than the ODR regimes around the grooves of the triple disc (16.8×10^{-8} g/cm^2/min), punch planter (17.1×10^{-8} g/cm^2/min) openers and surface broadcasting (16.8×10^{-8} g/cm^2/min). This situation was similar on day 14, except that the ODR regimes around the punch planter and surface broadcasting had increased to be not significantly different from the winged and hoe openers. This meant that the triple disc opener now showed significantly the lowest ODR regimes of all treatments on this day. By day 21 the ODR regimes in the vicinity of the grooves created by the winged (15.3×10^{-8} g/cm^2/min), hoe (14.9×10^{-8} g/cm^2/min), and power-till (14.7×10^{-8} g/cm^2/min) were significantly ($P<0.05$) higher than the ODR regimes in the vicinity of the grooves of the triple disc (12.9×10^{-8} g/cm^2/min), and punch planter (13.4×10^{-8} g/cm^2/min) openers together with surface broadcasting (13.2×10^{-8} g/cm^2/min).

The contrasting surface residue conditions had a significant ($P<0.05$) effect on ODR regimes on day 7, 14 and 21, but not on day 0. The presence of surface residue showed a significantly higher ODR regimes on days 7, 14 and 21 than the absence of surface residue. The magnitude of this difference, in fact increased with time.

The interactions between direct drilling seed sowing techniques and surface residue conditions did not show any consistent trends on day 0, but on days 7, 14 and 21 (with two exceptions; viz triple disc and hoe on day 7) the ODR regimes around the groove profiles in residue, regardless of the geometry of the grooves, were consistently higher than in no-residue conditions. These higher ODR values in residue might be attributed to increasing earthworm activity, with time (see Table 43).

Figure 44 shows the ODR regime changes for each seed sowing technique with time, under the contrasting crop residue conditions. It appears from all curves that between days 0 and 7 there was rapid reduction in mean ODR values under both contrasting residue conditions,

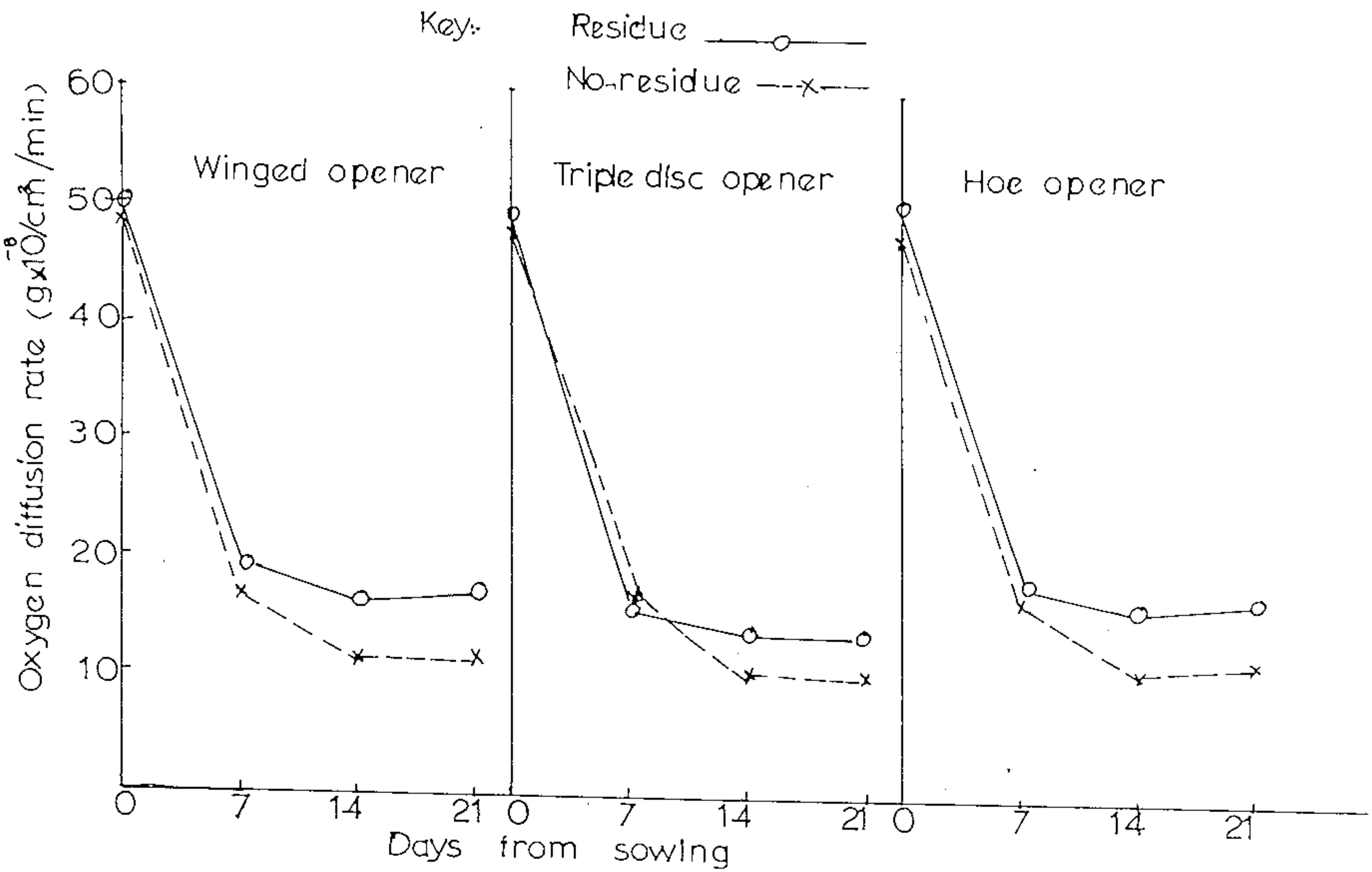


Figure 44: Effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on changes in oxygen diffusion rates (ODR) with time, in the presence of earthworms, under simulated rain conditions.(cont...

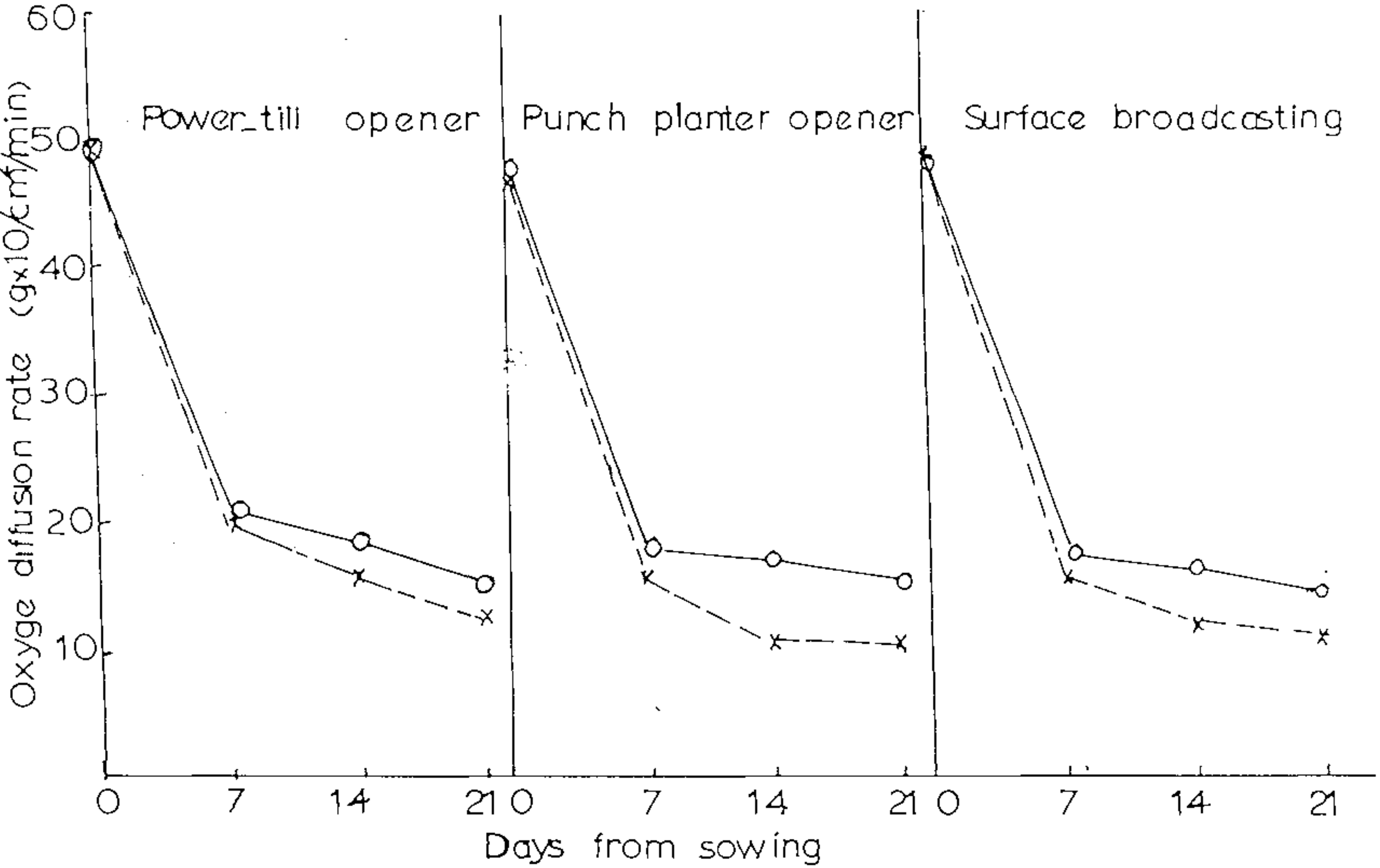


Figure 44 (cont...).

regardless of the geometry of the grooves. However, between days 7 and 21 (the terminal day), under residue, ODR regimes remained almost constant with the winged, triple disc and hoe openers, but continued to decline with the punch planter, power-till openers and surface broadcasting. No logical explanation for the slight decline of ODR regimes could be given, as earthworm activity under the residue was considered to be high. By contrast, under no-residue conditions, regardless of the geometry of the grooves and surface broadcasting, the ODR regime between days 7 and 21 was generally lower and continued to decline slightly compared with residue conditions.

Figures 45a-f are a family of iso-ODR lines which illustrate the average cumulative ODR data for days 7-21 for each groove and residue condition. As described in Section 3.2, the Figures are arbitrarily divided into three zones. The low ODR zone represents ODR values of 15 x 10^{-8} g/cm^{2}/min and below. The medium zone is 15-18 x 10^{-8} g/cm^{2}/min and the high zone represents ODR values of 18 x 10^{-8} g/cm^{2}/min and above.

The Figures show that the ODR zones under the constrasting residue conditions around the grooves of three openers, winged, triple disc and hoe were similar to those described in Section 3.2. For example, under crop residue conditions the medium ODR range extented down to 60-70 mm below the base of the grooves of the winged (Fig. 45a above) and hoe (Fig. 45c above) openers. By contrast, under no-residue conditions (Figures 45a and 45c below) the depth of the medium ODR zone was much shallower (30-45 mm) in these grooves. The width of the medium zones with the winged and hoe openers under both residue and no-residue conditions extended upto 90 mm either side of the groove centres (which was the limit of measurement). Both these openers showed a large zone of high ODR immediately beneath the grooves under residue conditions.

The grooves of the triple disc opener, extended the medium ODR zone down to only 13 mm and 40 mm in the residue (Fig. 45b above) and no-residue (Fig. 45b below) conditions respectively. The width of this zone was also very restrictive, being about 20 mm either side of the groove with no-residue and only 5 mm under residue conditions. The occurrence of a secondary medium ODR zone under residue conditions with the triple disc was thought to be of no consequence, as a zone of about 40 mm of low ODR separated the two medium ODR zones. The grooves of the

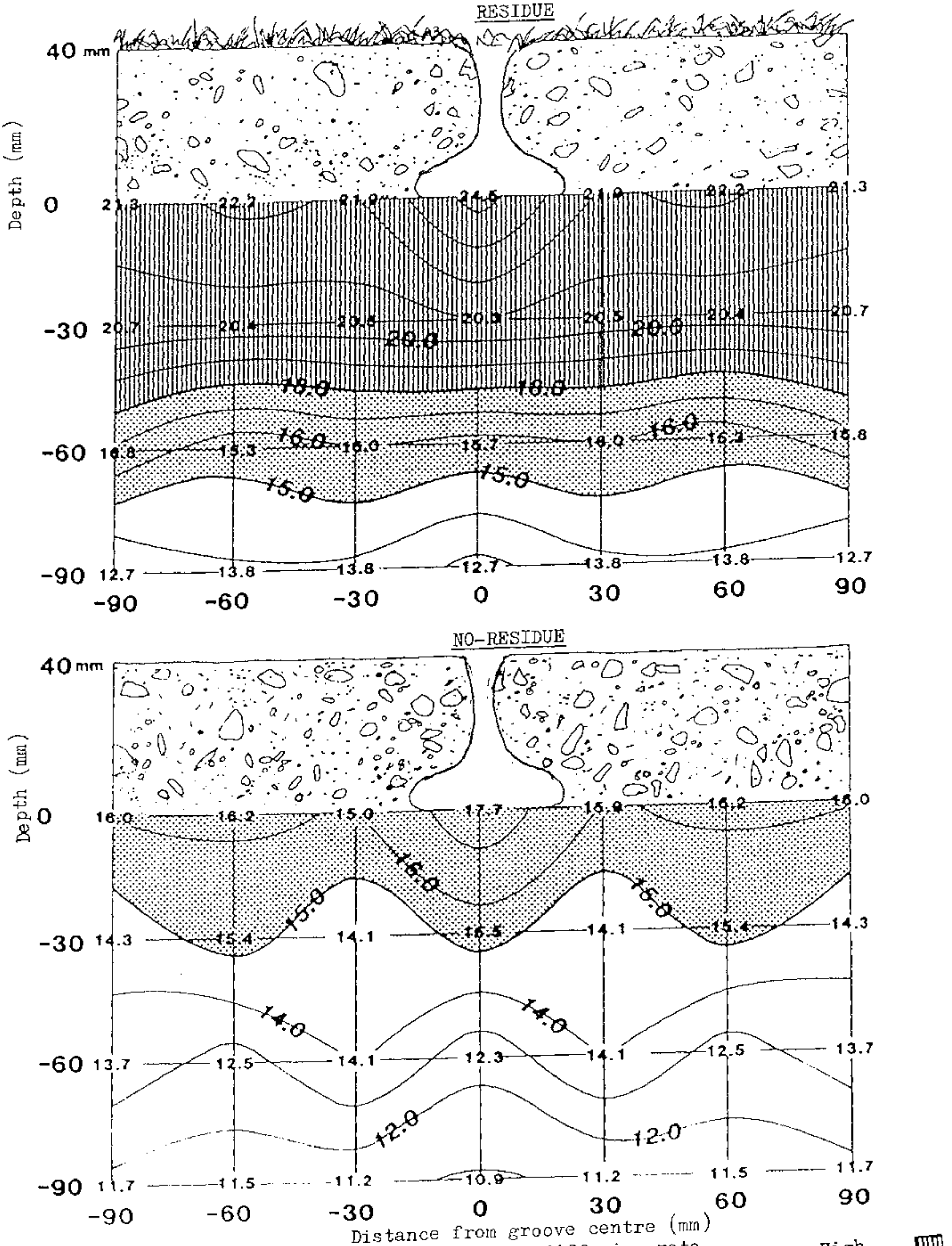


Figure 45a: Average cumulative oxygen diffusion rate zones, created around a direct drilled groove (Winged opener, days 7-21), under simulated rain conditions.

$(g \times 10^{-8}/cm^2/min)$

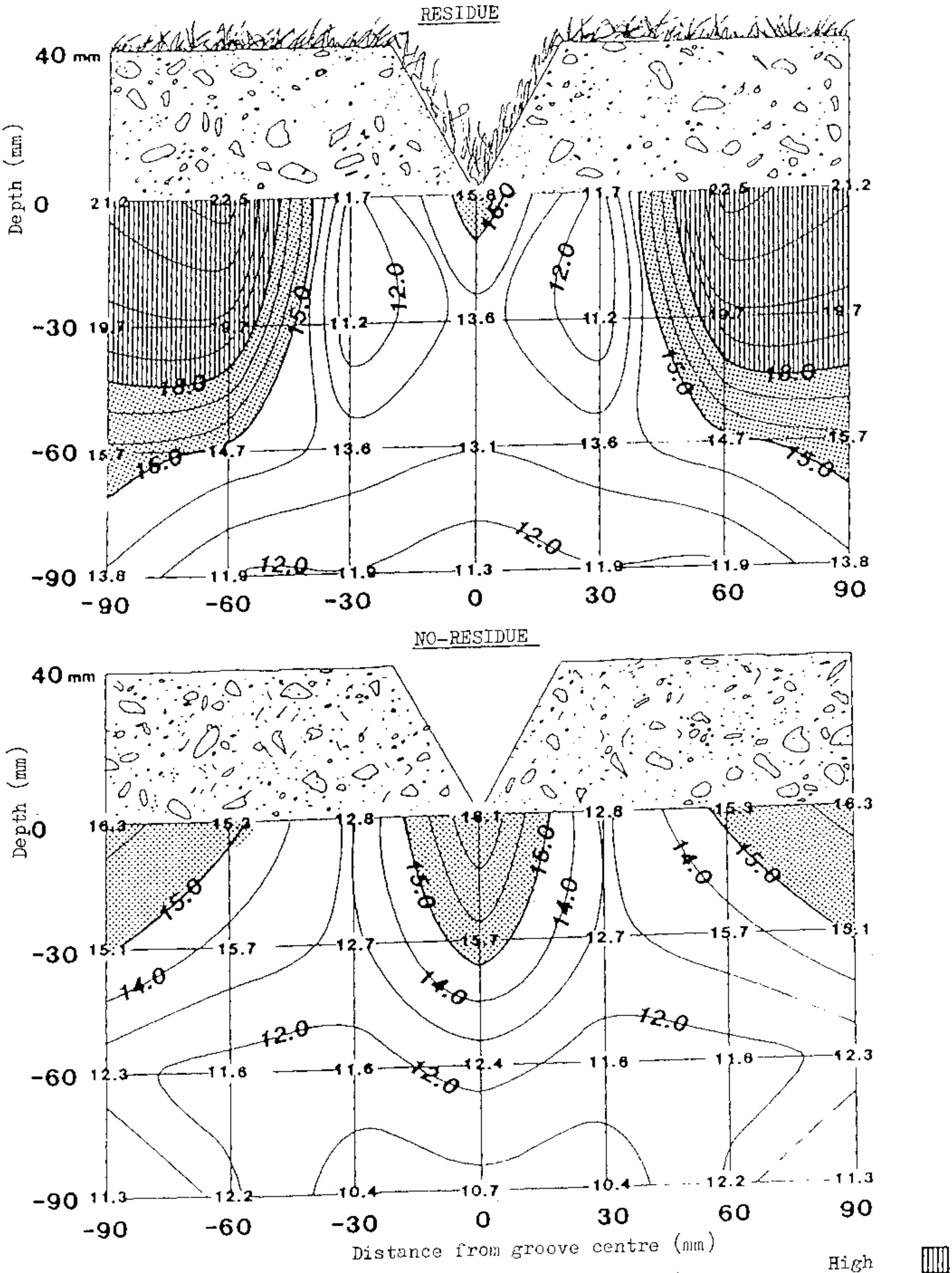


Figure 45b: Average **cumulative** oxygen diffusion rate zones, created around a direct drilled groove (Triple disc opener, days 7-21), under simulated rain conditions.

($gx10^{-8}/cm^2/min$)

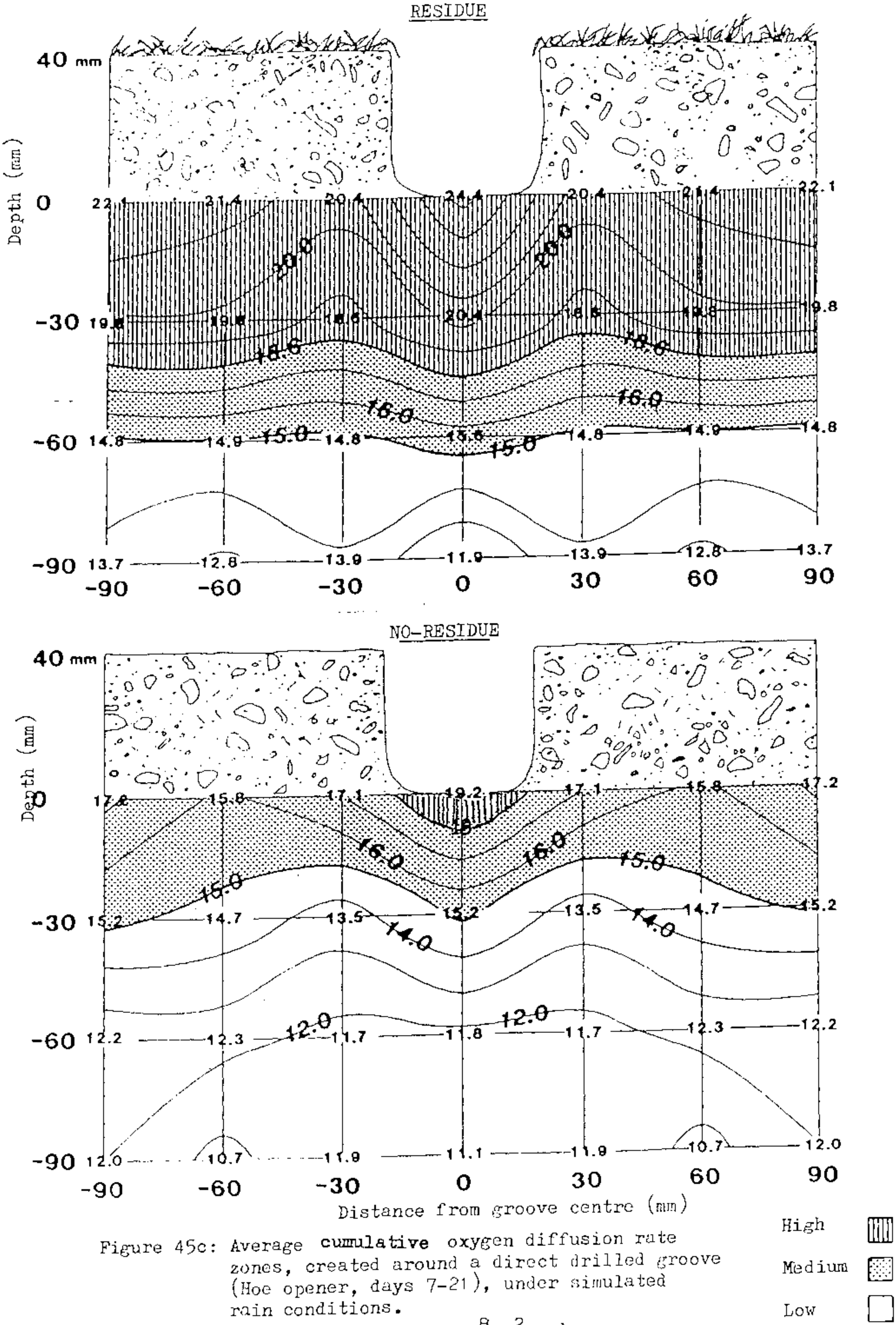


Figure 45c: Average **cumulative** oxygen diffusion rate zones, created around a direct drilled groove (Hoe opener, days 7-21), under simulated rain conditions.

$(g x 10^{-8} cm^{-2} min)$

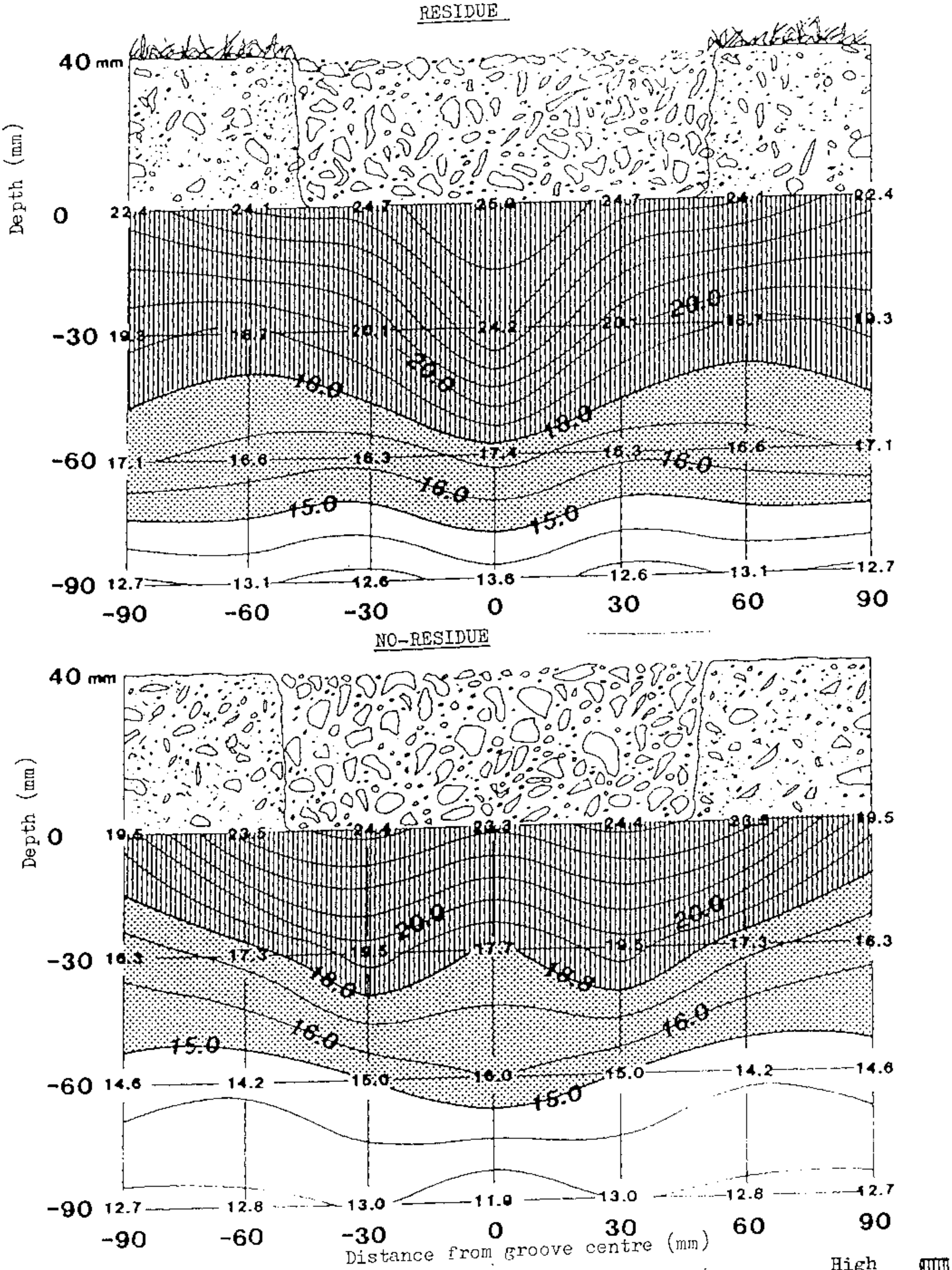


Figure 45d: Average **cumulative** oxygen diffusion rate zones, created around a direct drilled groove (**Power-till** opener, days 7-21), under simulated rain conditions.

$(g \times 10^{-8} cm^{-2}/min)$

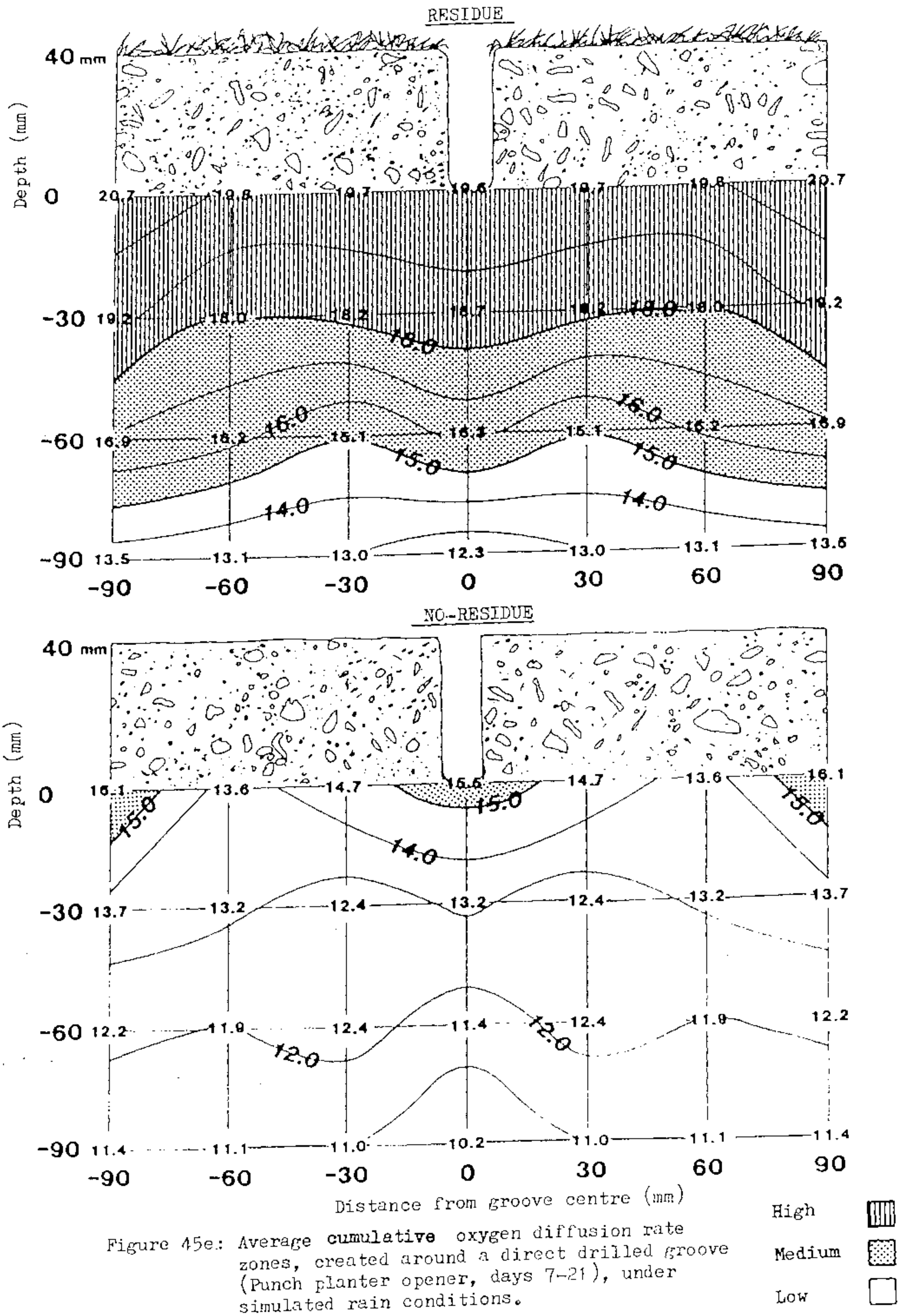


Figure 45e: Average **cumulative** oxygen diffusion rate zones, created around a direct drilled groove (Punch planter opener, days 7-21), under simulated rain conditions.

($g \times 10^{-8}\ cm^{-2}/min$)

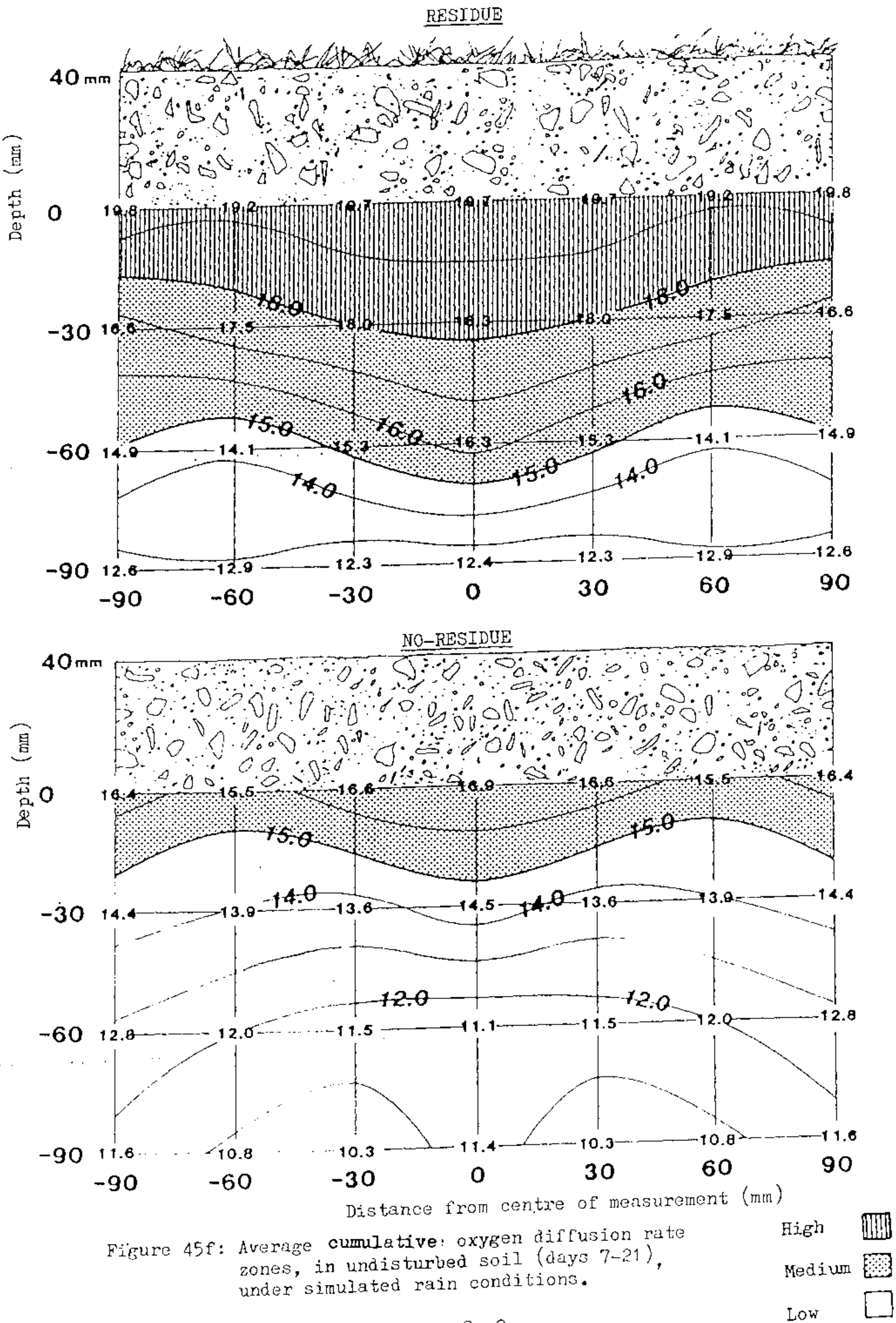


Figure 45f: Average **cumulative** oxygen diffusion rate zones, in undisturbed soil (days 7-21), under simulated rain conditions.

($g x 10^{-8} cm^{-2} min^{-1}$)

triple disc opener showed no zones of high ODR, except 50 mm to the sides of the grooves under the residue conditions, which was thought to be of no consequence as it was also isolated from the groove by a 40 mm zone of low ODR.

The depth of the medium ODR zones in the grooves of the power-till opener, extended to 75-80 mm and 50-70 mm below the base of the groove under residue (Fig. 45d above) and no-residue (Fig. 45d below) conditions respectively. Under both residue conditions, this opener showed large zones of high ODR immediately below the groove base. The zone of high ODR gradually became shallower as it extended from the centre of the groove and had a maximum width of 50 mm either side from the centre of the groove. The width of the medium ODR zone with this opener under both residue and no-residue conditions extended up to 90 mm either side of the groove centre (which was the limit of measurement).

The groove of the punch planter opener under residue conditions (Fig 45e above) extended the zone of medium ODR 60-75 mm down from the base of the groove. The width of this zone in residue extended to at least 90 mm either sides of the groove. This opener showed a high ODR zone immediately below the groove base under crop residue conditions. The punch planter opener showed a zone of medium ODR only 10 mm down from the centre of the groove in no-residue (Fig. 45e below) conditions. The width of this zone was very restrictive, being only about 20 mm either side of the groove. This medium ODR zone was totally encircled by a low ODR zone on both sides of the groove centre. Another small medium ODR zone started 80 mm away from the centre of the groove, but this zone was thought to be of no consequence as both medium ODR zones were isolated by about 60 mm of a low ODR zone in between.

In the undisturbed soil of the surface broadcasting treatment under residue conditions (Fig.45f above), the zones of medium and high ODR extended 50-70 and 20-35 mm respectively below this 40 mm point. The width of medium ODR zones extended at least 90 mm either side from the centre of the undisturbed area. Under no-residue (Fig. 45f below), the surface broadcasting treatment extended a medium ODR zone to only 10-25 mm below a point where seeds were deposited with the opener treatments (viz 40 mm below the soil surface). Surprisingly, the undisturbed soil surface had a larger zone of medium ODR value than the punch planter opener in no-residue. No logical explanation could be given for this.

Viewed as a family of curves the overall impression is that only the power-till and triple disc openers substantially altered the distribution of ODR zones, compared with the "undisturbed" soil under surface broadcasting. The response of the soil per.se. to surface residue was clear. Introduction of residue resulted in a high ODR zone, where a medium ODR zone, had been the maximum available in the absence of surface residue. Even then, the power-till opener had its major effect with no-residue, when it disturbed (aerated) a 100 mm wide zone and thus promoted an artificially high ODR zone where none existed with any of the other openers.

The effect of the triple disc opener was all negative. It clearly reduced porosity around the groove, which Mai (1978) had earlier demonstrated. The result was to isolate the groove itself from any beneficial effects which residue might have had on the soil, and in the absence of such residue, to do nothing to promote even a continuous zone of medium ODR which would have been the maximum available with no-residue.

Earthworm populations around
the groove profiles:

Table 41 shows the effects of direct drilling seed sowing techniques and contrasting surface residue conditions, on earthworm populations around the groove profiles, and the interactions between these two parameters. It appears from the Table , that the grooves of the winged (18.7), hoe (17.3), and power-till (18.7) openers together with surface broadcasting (18.0) had a significantly ($P<0.05$) higher number of earthworms around their grooves than was the case with the punch planter opener (14.2) which itself had significantly more earthworms than the triple disc opener (8.7).

The contrasting surface residue conditions had a significant ($P<0.05$) effect on earthworm populations around the groove profiles. The presence of surface residue encouraged significantly more earthworms (19.9) than where resiude was absent (11.9).

The interactions between seed sowing techniques and surface residue

Table 41: Effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on earthworm populations around the groove profiles, in the presence of earthworms, under simulated rain conditions.

Seed sowing techniques						Residue		Interactions							
Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broad-casting	NR*	R**	Seed sowing techniques/ Residue	Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broad-casting	
Populations per core***															
18.6 a	8.7 c	17.3 a	18.7 a	14.2 b	18.0 a	11.9 b	19.9 a	NR	12.7	8.0	12.7	14.3	10.0	13.7	SED1=2.06
								R	24.7	9.3	22.0	23.0	18.3	22.3	SED2=2.17

*NR = No surface residue present.
**R = Surface residue present.
*** Core volume=1.13 litres.
Unlike letters in a row denote significant differences (P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

Table 42: Effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on populations of earthworm species around the groove profiles, in the presence of earthworms, under simulated rain conditions.

Earthworm species	Seed sowing techniques						Residue		Interactions							
	Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broadcasting	NR*	R**	Seed sowing techniques/ Residue	Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broadcasting	
	Populations per core***															
A. longa	2.7 a	0.7 a	0.8 a	1.8 a	1.2 a	1.8 a	1.4 a	1.6 a	NR	2.3	1.3	0.0	1.7	1.0	2.0	SED1=0.96
									R	3.0	0.0	1.7	2.0	1.3	1.7	SED2=0.91
L. rubellus	9.7 a	5.2 a	9.8 a	8.8 a	7.5 a	6.0 a	5.5 b	10.2 a	NR	4.7	5.0	7.0	6.3	5.7	4.3	SED1=2.69
									R	14.7	5.3	12.7	11.3	9.3	7.7	SED2=3.04
A. caliginosa	6.3 b	2.8 c	6.7 ab	8.0 ab	5.5 b	10.2 a	5.0 b	8.2 a	NR	5.7	1.7	5.7	6.3	3.3	7.3	SED1=2.19
									R	7.0	4.0	7.7	9.7	7.7	13.0	SED2=2.17

*NR = No surface residue present.
**R = Surface residue present.
*** Core volume=1.13litres.
Unlike letters in a row denote significant differences (P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

conditions showed a consistent trend amongst all direct drilling seed sowing techniques (except the triple disc opener) towards greater numbers of earthworms under residue than under no-residue conditions.

Table 42 shows the effects of direct drilling seed sowing techniques and crop residue conditions, and the interactions between these two parameters, on the distribution of the three earthworm species (Allolobophora longa, Lumbricus rubellus, Allolobophora caliginosa) present in the undisturbed soil. The Table shows that direct drilling seed sowing techniques had no significant effects on numbers of Allolobophora longa and Lumbricus rubellus, but there appeared to be a significant effect of direct drilling seed sowing techniques on Allolobophora caliginosa. The triple disc opener grooves promoted the lowest numbers of this species. Surface broadcasting together with the hoe and power-till openers promoted the highest numbers of Allolobophora caliginosa. There appeared to be no significant differences amongst the grooves of the winged, hoe, power-till and punch planter openers with Allolobophora caliginosa.

The contrasting crop residue conditions had a significant effect on Lumbricus rubellus and Allolobophora caliginosa. Both species were more numerous under residue than with under no-residue conditions. However, the contrasting crop residue conditions had no significant effect on numbers of Allolobophora longa.

The interactions between direct drilling seed sowing techniques and crop residue conditions showed higher numbers of Lumbricus rubellus in the grooves of the winged, hoe and perhaps power-till openers in residue, than in no-residue conditions. Such results were similar to pot experiment 8. Allolobophora caliginosa responded positively to residue in the surface broadcasting treatment.

Area indices of earthworm activity:

The area indices of earthworm activity (the proportion of ground adjacent to the groove which was covered by earthworm holes and/or casts) were measured on days 7, 14 and 21. Table 43 shows the area indices of earthworm activity around the groove profiles, as a function of direct drilling seed sowing techniques and contrasting surface residue

Table 43: Effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on area indices of earthworm activity around the groove surfaces, in the presence of earthworms, under simulated rain conditions.

Days from sowing	Seed sowing techniques						Residue		Interactions							
	Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broad-casting	NR*	R**	Seed sowing techniques/ Residue	Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broad-casting	
			Area index***													
7	0.073 a	0.040 b	0.068 a	0.073 a	0.074 a	0.074 a	0.060 b	0.074 a	NR	0.060	0.046	0.062	0.063	0.063	0.066	SED1=0.0114
									R	0.086	0.034	0.074	0.082	0.084	0.081	SED2=0.0136
14	0.085 a	0.045 b	0.078 a	0.088 a	0.081 a	0.086 a	0.069 b	0.085 a	NR	0.072	0.046	0.064	0.079	0.073	0.078	SED1=0.014
									R	0.098	0.045	0.091	0.097	0.088	0.093	SED2=0.015
21	0.099 a	0.049 b	0.084 a	0.094 a	0.088 a	0.093 a	0.075 b	0.094 a	NR	0.085	0.048	0.069	0.083	0.079	0.084	SED1=0.0134
									R	0.112	0.050	0.098	0.105	0.098	0.101	SED2=0.0136

*NR = No surface residue present.
**R = Surface residue present.
*** Area of casts or earthworm holes (m^2)/0.12 m^2 soil surface area.
Unlike letters in a row denote significant differences (P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

conditions, and the interactions between these two parameters. The Table indicates significant ($P<0.05$) effects of direct drilling seed sowing techniques on the area indices. On each of the measuring days 7, 14 and 21 the grooves of the triple disc opener showed significantly lower area indices (day 21; 0.049) than all other grooves (day 21; winged, 0.099; hoe, 0.084; power-till, 0.094; punch planter, 0.088 and surface broadcasting, 0.093).

The contrasting surface residue conditions had a significant effect on area indices. On each of the measuring days 7, 14 and 21 the surface residue conditions showed a significantly higher area index than no-residue conditions.

The interactions between direct drilling seed sowing techniques and surface residue conditions emphasized the low level of earthworm activity around the groove profile of the triple disc opener in residue compared with all other direct drilling seed sowing techniques under residue conditions on all sampling days.

These data closely parallel the counts of earthworm populations, which suggests that the area indices of earthworm casts may be a reasonably accurate way of reflecting populations as well as activity.

Soil bulk density around
the groove profiles:

Table 44 lists the effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on soil bulk density around the groove profiles, and the interactions between these two parameters. It appears from the Table that the grooves of the triple disc opener showed a significantly ($P<0.05$) higher bulk density (1.25 g/cm^3) than the grooves of the power-till (1.20 g/cm^3), punch planter (1.21 g/cm^3) openers, together with surface broadcasting (1.21 g/cm^3), which were themselves significantly higher than the grooves of the winged (1.16 g/cm^3) and hoe (1.17 g/cm^3) openers. The latter two openers were not significantly different.

The contrasting surface residue conditions had a significant ($P<0.05$) effect on the soil bulk density around the groove profiles. The

Table 44: Effects of direct drilling seed sowing techniques and contrasting crop residue conditions, on soil bulk density and soil moisture content around the groove profiles, in the presence of earthworms, under simulated rain conditions.

	Seed sowing trechniques						Residue		Interactions							
	Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broad-casting	NR*	R**	Seed sowing techniques/ Residue	Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broad-casting	
soil bulk density (g/cm^3)	1.16 c	1.25 a	1.17 c	1.20 b	1.21 b	1.21 b	1.23 a	1.17 b	NR	1.20	1.27	1.21	1.22	1.23	1.23	SED1=0.008
									R	1.12	1.23	1.13	1.17	1.19	1.18	SED2=0.007
Soil moisture content (% d.b)	32.7 d	34.2 a	33.1 cd	32.8 d	33.7 b	33.4 bc	33.7 a	32.9 b	NR	33.2	34.4	33.5	33.0	34.5	33.9	SED1=0.249
									R	32.2	34.0	32.7	32.6	33.0	32.9	SED2=0.192

*NR = No surface residue present.
**R = Surface residue present.
Unlike letters in a row denote significant differences (P<0.05).
SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

crop residue conditions showed a significantly lower soil bulk density (1.17 g/cm^3) than the no-residue conditions (1.23 g/cm3).

The interactions between direct drilling seed sowing techniques and crop residue conditions confirmed the main and subtreatment effects, with a consistent trend of lower soil bulk density around the groove profiles in residue, with each opener. The triple disc opener, both in residue and no-residue displayed the highest soil bulk density of all treatments which might confirm the data of Mai (1978).

Soil moisture content (% d.b.)
around the groove profiles.

Table 44 also shows the effect of direct drilling seed sowing techniques and contrasting crop residue conditions, on soil moisture content around the groove profiles, and the interactions between these two parameters. It appears from the Table, that the grooves of the triple disc opener were slightly but significantly ($P<0.05$) wetter (34.2%) than the grooves of all other direct drilling seed sowing techniques. The next wettest group of grooves were those of the punch planter opener (33.7%) and surface broadcasting (33.4%). This was followed by a group containing the hoe (33.1%), winged (32.7%) and power-till (32.8%) openers. The grooves in the latter group were not significantly different. There were no significant differences between the "grooves" of the punch planter and surface broadcasting; nor between surface broadcasting and the hoe opener.

The contrasting surface residue conditions had a significant ($P<0.05$) effect on soil moisture contents (% d.b.) around the groove profiles. The no-residue conditions showed slightly but significantly ($P<0.05$) higher soil moisture contents (33.7%) than residue conditions (32.9%).

The interactions between opener types and crop residue conditions appeared to confirm the main and subtreatment effects (with the possible exception of the triple disc and power-till openers) of reduced soil moisture contents in the presence of residue.

3.6.5 Discussion of Experiments 10 and 11

Although these two experiments were conducted separately, the soil, direct drilling seed sowing techniques, residue, ambient temperatures and simulated rainfall were as nearly identical as possible. The experiments were conducted under controlled climatic conditions for this reason. The two experiments are, therefore, compared and contrasted below. The combined impressions of these two experiments are:

1. The effects of direct drilling seed sowing techniques in the absence and presence of earthworms were confirmed (insofar as the winged, triple disc and hoe openers were concerned), together with an almost predictable extension of these principles for three further seed sowing methods.

2. A high level of agreement was noted between measurements of seedling emergence, ODR regimes, earthworm numbers and activity, and soil bulk densities, in reflecting treatment differences.

Most of the comparable results of Experiment 10 (in the absence of earthworms) were similar to those of Experiment 7 (Section 3.4) described earlier (also in the absence of earthworms) under simulated rain conditions. Experiment 10 compared a wider range of direct drilling seed sowing techniques, than Experiment 7, including surface broadcasting, power-till and punch planter openers. Unlike Experiment 7, however, (or because of the increased treatment numbers) the effects of the major treatment factor (direct drilling seed sowing techniques) did show some significant differences in seedling emergence, seed fate, root/shoot weights and ODR regimes, although there were still no differences in soil bulk densities and soil moisture contents around the groove profiles.

The power-till, punch planter openers and surface broadcasting treatments were introduced to examine treatments which might have been expected to represent the extreme ends of the range. The power-till and surface broadcasting treatments were expected to introduce high levels of ODR, while with the punch planter, which disturbed the soil the least but still buried the seeds, ODR might have been low. The power-till disturbed a wider than usual zone of soil (100 mm).

Perhaps, therefore, in the absence of earthworms, it was not surprising that the surface broadcasting treatment showed the highest level of seedling emergence (89%). In the absence of earthworms, the rates of emergence from the power-till grooves and surface broadcasting during the first five days were also higher than all other direct drilling seed sowing techniques. Clearly the surface broadcasted seeds were exposed to the maximum atmospheric oxygen and under the simulated rain there was always sufficient moisture for rapid germination of seeds and seedling emergence. Similar reasoning (although with a reduced availability of atmospheric oxygen) could be applied to the grooves of the power-till opener. The surface broadcasting treatment, however, could not be expected to form the basis of a commercial practice for untilled soils to sow cereals in variable climates, because of the unreliable precipitation moisture supply that could be expected to occur in the field. It should also be noted that under the experimental conditions, seeds were deliberately placed under the residue on the soil surface (using forceps) which could not be expected to be realistically duplicated in the field. The power-till opener on the other hand, could be viewed as something close to a fully tilled seed-bed, or at least as strip tillage.

In contrast to the above results, in the presence of earthworms the two major treatment factors (direct drilling seed sowing techniques and contrasting crop residue conditions) had significant effects on seedling emergence, seed fate, root/shoot weights, ODR regimes, earthworm populations and their activity, soil bulk densities and soil moisture contents around the groove profiles. Seedling emergence, in general, was lifted markedly by the presence of earthworms, and in many cases could be considered highly satisfactory from a practical stand point. For example, surface broadcasting (both with and without residue) and the winged opener with residue, promoted more than 75% seedling emergence. A group of treatments including the power-till opener (with and without residue) and the hoe opener with residue promoted more than 60% emergence. These results were similar to the experiments (2, 3 and 8) reported earlier. The reasons for the good and poor responses, particularly in the grooves of the winged, triple disc and hoe openers, might also have been similar to those already discussed (i.e. interactive effects of earthworm channels, ODR regimes and the position of surface residue). Figures 46 (a-f) show the effects on seed/seedling

a

b

Figure 46 (a, b): Effects of opener types on barley seedling emergence in the absence of earthworms, under simulated rain conditions.

Note poor performance in the grooves of triple disc (TD), punch planter (narrow U) and winged (chisel) openers. Note also good emergence with broadcasting (broad C).

c

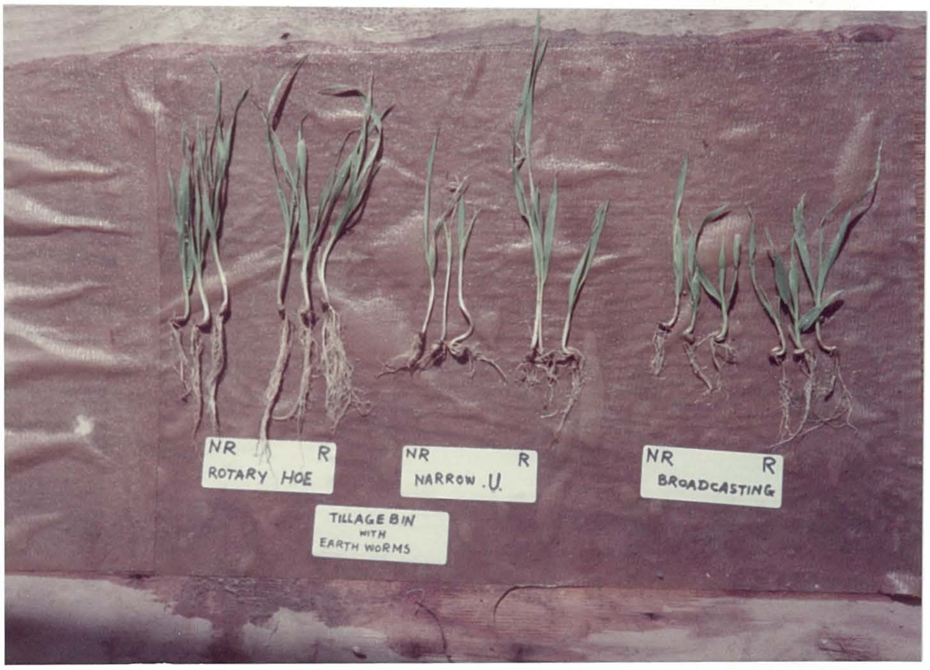
d

Figure 46 (c, d): Effects of opener types on barley seedling emergence in the presence of earthworms, under simulated rain conditions.

Note poor performance in the grooves of triple disc (TD) and punch planter opener (Narrow U) openers.

CHISEL = Winged opener; TD= Triple disc opener; Hoe = Hoe opener; RH = Power-till opener; NARROW U = Punch planter opener; BROADC = Surface broadcasting.

e



f

Figure 46 (e, f): Typical seedlings from direct drilled grooves in the presence of earthworms, under simulated rain conditions.

NR= No-residue; R= Residue.

Chisel = Winged opener; Trip.Disc = Triple disc opener; Hoe = Hoe opener; Rotary Hoe = Power-till opener; Narrow U = Punch planter opener; Broadcasting = Surface broadcasting.

performance, of direct drilling seed sowing techniques and crop residue conditions in the absence and presence of earthworms.

The figures illustrate:

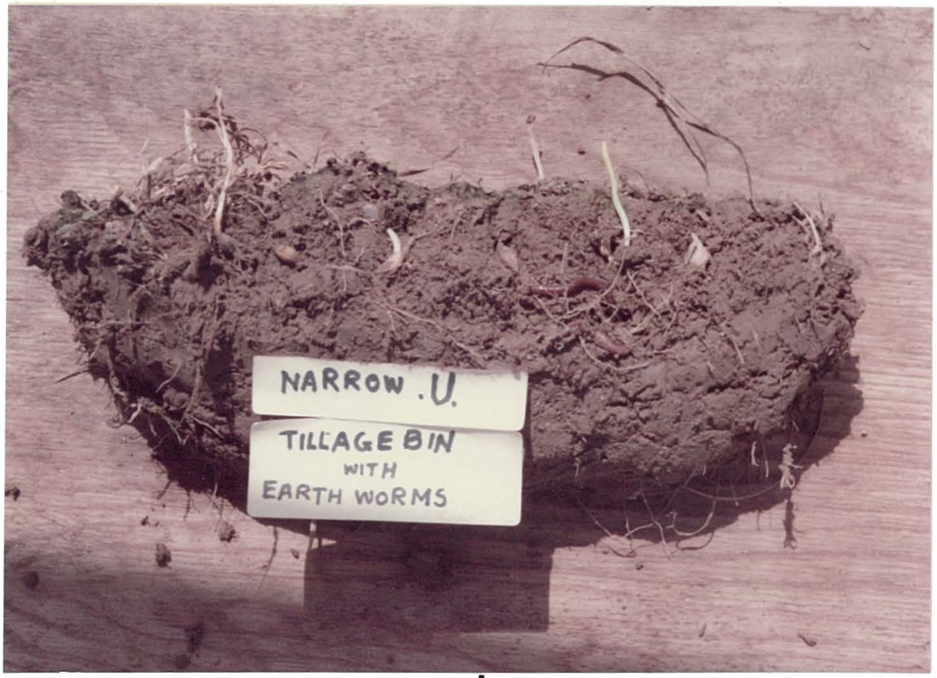
Figures 46 (a and b): Poor barley seedling performance in the absence of earthworms.

Figures 46 (c and d): Favourable performance of barley seedlings in the presence of earthworms.

Figures 46 (e and f): The contrasting root and shoot performances of barley seedlings in response to different direct drilling seed sowing techniques in the presence of earthworms.

Comparing experiments (10 and 11), surface broadcasting of seeds and the use of the punch planter opener, showed almost no response (in terms of seed germination and seed fate) to the presence or absence of earthworms. The grooves of the power-till opener promoted approximately 20% more seedling emergence in the presence of earthworms than in the absence of earthworms. In the presence of earthworms the grooves of the winged and hoe openers promoted almost 3 times more seedling emergence than in the absence of earthworms. Similarly, the grooves of the triple disc opener promoted only a small level of seedling emergence, in the presence of earthworms compared with the absence of earthworms. This suggests that there were both direct and interactive effects of earthworms on seed germination and seedling growth. Perhaps the unresponsive performance of the punch planter in the presence of earthworms might have been the result of the discrete holes which it formed (11 mm in dia) with the seed deposited at their bases. These holes were observed to fill with water and the seed remained submerged during simulated rain conditions. This pooling might have counteracted possible effects from the activity of earthworms. Figures 47 (a,b) show the effects of earthworms on seed germination and seedling emergence in the "grooves" of the punch planter opener. Figure 47a shows an increased number of ungerminated or dead seeds in the absence of earthworms. Figure 47a also illustrates that the shape of the "grooves" remained undisturbed in the absence of earthworms, where as the presence of earthworms (fig. 47b) shows that their activity had destroyed the

a



b

Figure 47 (a, b): Dissections of typical punch planter "groove", (a) without earthworms (b) with earthworms. Note the less aerated àppearance without earthworms. (Narrow U = Punch planter opener) original shape of the holes.

In contrast to the non-earthworm situation, in the presence of earthworms, there appeared to be strong interactions between direct drilling seed sowing techniques and contrasting crop residue conditions. The crop residue conditions consistently benefitted the winged and hoe openers (in terms of seedling emergence performance). It is interesting that the power-till opener showed practically no response to residue conditions in the presence of earthworms. An explanation for this might be that the power-till opener incorporated the crop residue in the soil. Either this diluted its influence to be little different than bare cultivated soil, or there may have been some adverse effects of phytotoxicity from the incorporated decomposing crop residue as has been reported under cooler climatic conditions of England (Lynch, 1978; Lynch et al 1980). In addition some mortality of earthworms could have occurred. On the other hand, a much smaller proportion of seeds would have had intimate contact with the residue in this way in the power-till groove, with its pulverised soil, than had appeared to be the case in the triple disc opener, which nevertheless, behaved in a similar manner to the power-till opener. Only the winged and hoe openers were observed to separate residue from intimate contact with the seed.

It appears from a comparison in the absence and presence of earthworms that ODR regimes between days 7-21 across all direct drilling seed sowing techniques, in the presence of earthworms, were almost 3 fold higher than in the absence of earthworms, under both residue and no-residue conditions.

The geometry and characteristics of the individual direct drilled grooves (excluding surface broadcasting) appeared also to create differences in ODR values amongst direct drilling openers under the contrasting crop residue conditions and in the absence and presence of earthworms. For example, in the absence of earthworms and in both residue conditions, the ODR values around the grooves of the power-till opener were almost 50% higher than the grooves of the other opener types between days 7-21. Even so these ODR values were almost 50% below the minimum requirement for barley (15×10^{-8} $g/cm^2/min$; See review of literature). Similarly, in the presence of earthworms the ODR values around the grooves of the power-till opener appeared to be significantly

a

b

Figure 48 (a, b): Typical grooves created by triple disc opener in the presence and absence of earthworms.

Note the more crumbled nature of the groove created in the presence of earthworms.

higher than any other opener types in no-residue conditions, which might have resulted in higher seedling emergence than other true openers.

The triple disc grooves (with compaction and smearing on the sides and bases of the grooves) and the punch planter "grooves" (with narrow "U" shaped discrete holes allowing accumulated water) showed the lowest ODR regimes of all opener types on most of the measuring days. This might have been partially responsible for their low seed/seedling performances.

Figures 48 (a,b) illustrate the areas around the surface of a triple disc opener groove in the presence (fig. 48a) and absence (Fig. 48b) of earthworms. Figure 48b shows particularly, the undisturbed compacted groove created by the opener in the absence of earthworms. In the presence of earthworms (Fig. 48a) the effect of compaction was not so evident.

The wide range of direct drilling seed sowing techniques tested under contrasting crop residue conditions in the absence and presence of earthworms in these two experiments showed that in the absence of earthworms the exposure of seed to atmospheric oxygen (such as with the power-till and surface broadcasting) gave high seedling emergence counts. In the presence of earthworms, although surface broadcasting continued to promote high seedling emergence, those openers with shattered grooves and residue over the top of the grooves (such as with the winged opener) or residue remaining in the vicinity of the grooves (such as with the hoe opener) benefitted, in terms of seedling emergence performances, by the presence of crop residue. Residue inside a compacted and/or smeared groove (triple disc opener) or over the top of the "groove" with puddled water inside the "groove" (punch planter opener) might have been partially disadvantaged (in terms of seed germination and seedling emergence) in both the presence and absence of earthworms.

3.7 EFFECTS OF SMEARING AND SOIL COMPACTION ON EARTHWORM ACTIVITY AND OXYGEN DIFFUSION RATES

3.7.1 Introduction:

In earlier experiments, it had been noted that soil bulk density around the groove profiles of the triple disc opener was significantly higher than that around the groove profiles of the winged, hoe, power-till and punch planter openers. Mai (1978) reported that under drying soil conditions earthworm populations around the groove profiles of the winged and triple disc openers were not significantly affected by soil bulk density or opener treatments after 21 days. However, when climatic conditions became more moist (due to heavy rainfall) the winged opener grooves showed a significantly larger number of earthworms than the triple disc opener grooves after 35 days. Mai did not attempt to explain the reason for this effect.

Earlier experiments in this report confirmed the findings of Mai (loc.cit). Lower numbers of earthworms were found around the groove profiles of the triple disc opener compared with the other openers used, which included the winged opener. It was also observed that the grooves of the triple disc opener showed a lower area index (discussed in Section 3.6) of earthworm activity compared with the winged, hoe, power-till and punch planter openers, and with surface broadcasting, both under residue and no-residue conditions. It seemed likely that this was the result of differences in soil compaction around the grooves, but no attempt was made to verify this. Little information was also available about earthworm activity in a drying soil. Experiments reported herein studied the response to smear or compaction of earthworm activity inside the soil. Their activity at the soil surface was observed by counting earthworm holes and castings on the soil surface. In addition little information was available regarding the effects of smears or compaction on earthworm activity while they were congregated on the surface of the soil, such as might occur when they entered the interior of a drilled groove.

Three experiments were therefore conducted, with the following objectives:

Experiment 12:

To study the effects of soil smearing and compaction on earthworm populations and their activity, together with ODR in a continuously wet soil.

Experiment 13:

To study earthworm populations and their activity in response to smearing and compaction in a drying soil.

Experiment 14:

Examination of the effects of soil surface smearing on the activity of earthworms congregated on the soil surface.

3.7.2 Effects of soil smearing and compaction on earthworm populations and activity (Experiment 12)

(a) Materials and methods:

A bare soil surface in the experimental field of Tokomaru silt-loam soil was compacted to three different soil bulk density levels (1.0 g/cm^3, 1.2 g/cm^3 and 1.4 g/cm^3) by using a heavy steel roller. The bare soil surface had been created by removing all residual plant material 8 weeks earlier, and the soil moisture content was 29% (d.b). From each compacted zone of undisturbed soil, samples (160 mm wide x 160 mm long x 200 mm deep) were cut with a spade and placed in plastic pots of the same size. All the pots were shifted to a glasshouse and were arranged in a completely randomised block design with three replicates. Three levels of smear (zero, light and heavy smear) were created on the surface of the soil using the back of a spatula. No drilled grooves were made. "Light" smearing of the surface resulted from rubbing the spatula over the soil surface twice and "heavy" smearing, by rubbing five times. No quantitative measurements of intensity of smearing were attempted.

The soil blocks were a 'snug' fit in the pots and the surface edges against the pots were sealed with molten wax, so that earthworms could reach the atmosphere only through the horizontal surface. To ensure a reasonable level of earthworm activity, crop residue was placed over the surface of all the pots after they had been smeared. Simulated rain conditions of 5 mm per hour for 4 hours per day were created by using a soak hose as described earlier. The glasshouse temperature was maintained at 15-20 ^{o}C day and night. It was clear that the residual earthworm populations in the plots were reasonably uniform (since uniform casting was observed) although specific populations were expected to be relatively low because the soil had not been residue-covered for 8 weeks.

Daily measurements of accumulated numbers of earthworm holes in the soil surface of the pots were taken for 21 days. For this purpose small map pins with round colour-coded heads were used. The map pins were placed in the earthworm holes, with new pins with heads of a different colour being placed in new holes at each observation. In this way sequential sampling of numbers of earthworm holes were made daily for 21 days. Statistical analyses of cumulative numbers of holes were made on days 1, 7, 15 and 21.

Measurements of ODR at a depth of 40 mm were taken on days 1, 7, 15 and 21. The ODR values were the average of two randomly selected points. The holes made by electrodes at each ODR measurement were filled with a slurry. On the final day, the soil blocks were removed and divided into two depth portions, 0-60 mm and 60-200mm. Numbers of earthworms (total of all species) were counted in each soil portion, by hand sorting.

(b) Results and discussion:

Cumulative numbers of earthworm holes:

Table 45 shows the effects of smearing intensity and soil bulk density levels, on cumulative numbers of earthworm holes, and the interactions between these two parameters. It appears from the Table, that there were small but significant ($P<0.05$) effects of smear intensity on numbers of earthworm holes on the soil surface on day 1. The pots with "zero" smear showed significantly higher numbers of earthworm holes (5.4) than the pots with "heavy" smear (3.6), but were not significantly

Table 45: Effects of smearing intensity and soil bulk density, on cumulative numbers of earthworm holes, under simulated rain conditions.

Days	Smear			Bulk density (g/cm^3)			Interactions				
	Zero	Light	Heavy	1.0	1.2	1.4	Bulk density/ Smear	1.0	1.2	1.4	
	Holes per pot*										
1	5.4	4.2	3.6	8.8	3.0	1.4	Zero	12.3	3.3	0.7	
	Aa	Aab	Ab	Aa	Bb	Cc	Light	7.7	3.0	2.0	SED=1.216
							Heavy	6.2	2.7	1.7	
7	35.2	26.4	16.8	49.6	26.4	16.8	Zero	59.3	29.3	17.0	
	Aa	Bb	Bc	Aa	Bb	Bc	Light	54.0	30.7	17.7	SED=6.43
							Heavy	35.3	19.3	15.7	
15	57.1	48.2	34.1	79.9	38.0	21.6	Zero	103.3	45.3	22.7	
	Aa	ABb	Bc	Aa	Bb	Cc	Light	83.3	40.0	21.3	SED=8.46
							Heavy	53.0	28.7	20.7	
20	64.7	51.1	37.7	91.8	39.6	22.1	Zero	120.7	49.7	23.7	
	Aa	ABb	Bc	Aa	Bb	Cc	Light	92.0	40.0	21.3	SED=8.55
							Heavy	62.7	29.0	21.3	

* Pot surface area=0.0256 m^2
Unlike letters in a row denote significant differences.
(Upper case, $P<0.01$; lower case $P<0.05$).
SED=Standard error of all interactive differences.

different from the "light" smear (4.2). However, on all subsequent sampling days there appeared to be increasing and significant ($P<0.05$) differences in the numbers of earthworm holes amongst pots between, on the one hand, "light" and "heavy" smears, and on the other hand, "zero" and "light" smears. The cumulative data on day 21 were; "zero" (64.7), "light" (51.1), "heavy" (37.7).

The contrasting soil bulk density levels had highly significant ($P<0.01$) effects on cumulative numbers of earthworm holes throughout the experiment. The soil surface overlying a bulk density of 1.0 g/cm^3 on the terminal day, showed the highest number of cumulative numbers of earthworm holes (91.8) compared with a soil bulk density of 1.2 g/cm^3 (39.6) which itself was significantly higher than where bulk density had been 1.4 g/cm^3 (22.1).

It appears from the Table, that there were strong interactions between smearing intensities and soil bulk densities. The combination of "zero" smear and soil bulk density of 1.0 g/cm^3 had clearly the highest cumulative numbers of earthworm holes (terminal, 120.7). Conversely, the combination of heavy smear and a soil bulk density of 1.2 or 1.4 g/cm^3 showed the lowest cumulative numbers of earthworm holes (terminal, 29.0 and 21.3 respectively), although at the higher level of soil bulk density (1.4 g/cm^3), the three levels of smearing had little additional effect on reducing the earthworm activity. In fact, throughout the experiment, bulk density appeared to have a greater effect on numbers of earthworm holes than the intensity of smearing.

Figures 49 (a,b,c) show the effects of smear intensities and soil bulk density levels under continuously wetting soil conditions. Each coloured pin-head represents an earthworm channel visible at the surface. The detrimental effect on earthworm activity of a high soil bulk density level (1.4 g/cm^3), regardless of smearing intensity, is illustrated in Figure 49c, by the low number of pins in all pots. An intermediate effect, of soil bulk density at 1.2 g/cm^3 is shown in Figure 49b, and a favourable effect of a soil bulk density level of 1.0 g/cm^3 is clearly illustrated in Figure 49a.

Figure 50 shows the effects of soil compaction levels and intensities of smear, on the rate of increase of numbers of earthworm

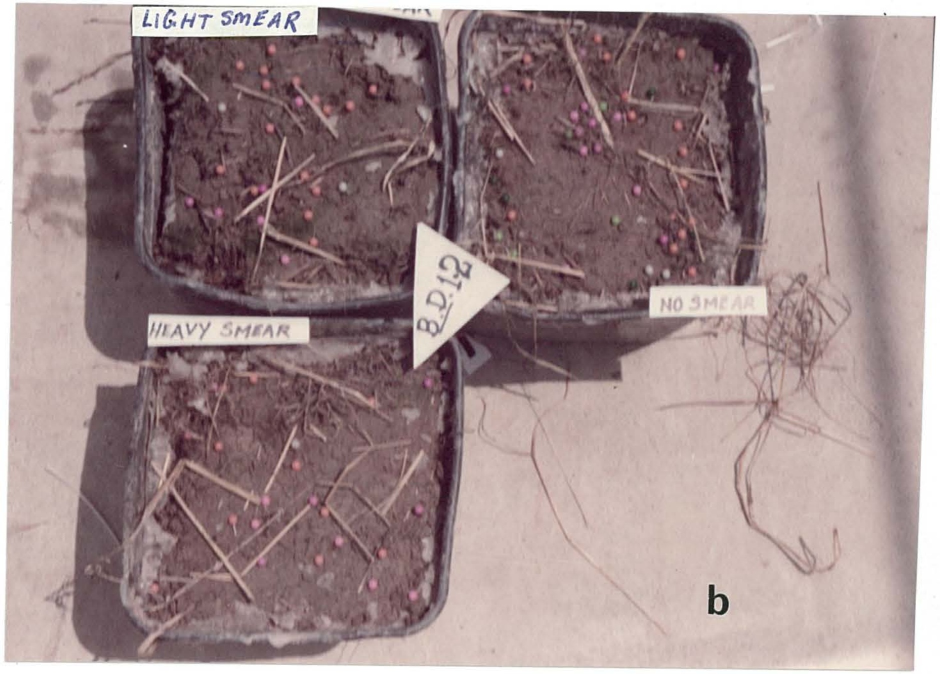


Figure 49 (a, b, c): Effects of smearing intensities and soil compaction levels on earthworm activity (**cumulative** numbers of earthworm holes).

(a). Soil bulk density level 1.0 g/cm^3
(b). Soil bulk density level 1.2 g/cm^3
(c). Soil bulk density level 1.4 g/cm^3

Note that the combition of "heavy" smear and soil bulk density 1.4 g/cm^3 (c) had the most adverse effect on earthworm activity.

(Round colour-coded map pins represent earthworm holes)

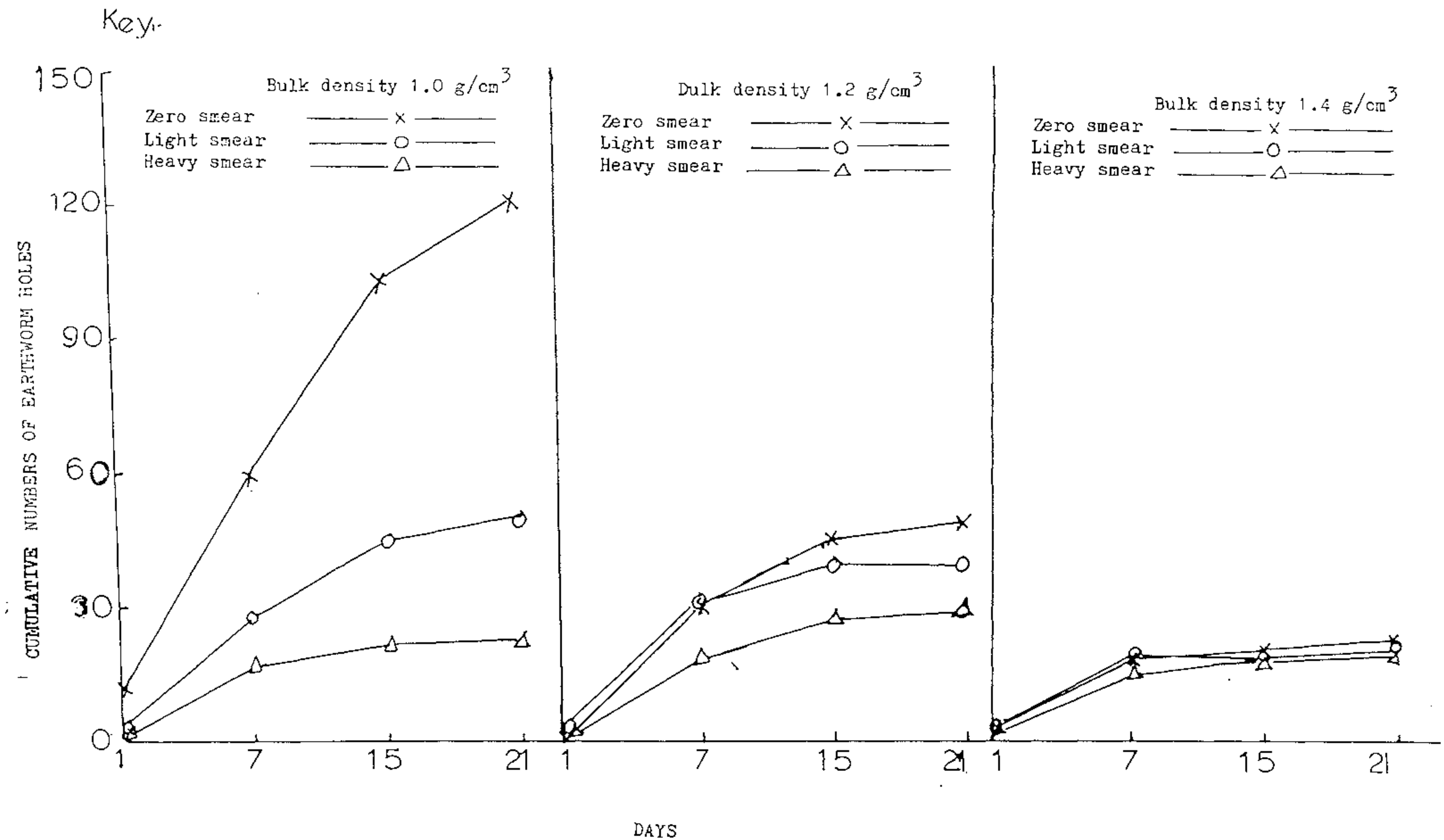


Figure 50: Effects of soil compaction levels and smearing intensities on **cumulative** numbers of earthworm holes under simulated rain conditions.

holes with time. The curves illustrate that differences in the rate of increase were greatest in the lowest soil bulk density (1.0 g/cm^3) and decreased with increasing bulk density, to be negligible with the highest soil bulk density of 1.4 g/cm^3. The curves also show that as soil bulk density was raised the rates of increase of earthworm holes of all three smear levels decreased, to be almost negligible after day 7 with the 1.4 g/cm^3 bulk density.

Oxygen diffusion rate (ODR):

Table 46 shows the effects of smearing intensity and bulk density level on ODR, and the interactions between these two parameters. It appears from the Table, that there were significant ($P<0.05$) effects of levels of smear on ODR measurements. On day 1, the pots with "zero" smear showed clearly the highest ODR regime ($23.3x10^{-8}$ $g/cm^2/min$) followed by the "light" smear ($14.4x10^{-8}$ $g/cm^2/min$). ODR in the pots with the "heavy" smear was only $8.3x10^{-8}$ $g/cm^2/min$. Perhaps surprisingly, these differences decreased with time. On day 7, the "zero" smear still had a significantly higher ODR regime ($13.1x10^{-8}$ $g/cm^2/min$) than the "heavy" smear ($8.6x10^{-8}$ $g/cm^2/min$), but neither was significantly different than the "light" smear on that day. Although the significant differences amongst the treatments were re-established on day 15. On day 21, only the pots with "zero" smear ($14.2x10^{-8}$ $g/cm^2/min$) had a significantly higher ODR than any other treatment. The "light" and "heavy" smears were not significantly different.

Table 46 also shows significant effects of soil bulk density ($P<0.05$) levels on the ODR regimes on days 1, 7, 15 and 21. On days 1, 7 and 15 the pots with a soil bulk density of 1.0 g/cm^3 showed significantly ($P<0.05$) higher ODR regimes than the pots with a soil bulk density of 1.2 g/cm^3, which were themselves significantly higher than the pots with a bulk density of 1.4 g/cm^3. The magnitude of these differences appeared to decrease with time, and on day 21, while the ODR regime with a soil bulk density of 1.0 g/cm^3 ($12.2x10^{-8}$ $g/cm^2/min$) was still significantly ($P<0.05$) higher than the ODR with soil bulk density of 1.2 g/cm^3 ($7.2x10^{-8}$ $g/cm^2/min$), the latter was not significantly different than where the bulk density had been 1.4 g/cm^3 ($5.8x10^{-8}$ $g/cm^2/min$).

Table 46: Effects of smearing intensity and soil bulk density, on oxygen diffusion rate (ODR), under simulated rain conditions.

Days	Smear			Bulk density (g/cm^3)			Interactions				
	Zero	Light	Heavy	1.0	1.2	1.4	Bulk density/ Smear	1.0	1.2	1.4	
	ODR ($g \times 10^{-8}/cm^2/min$)										
1	23.3	14.4	8.3	24.4	13.3	8.3	Zero	40.0	21.7	8.3	
	Aa	Bb	Cc	Aa	Bb	Bc	Light	20.0	11.7	11.7	SED=3.53
							Heavy	13.3	6.7	5.0	
7	13.1	11.1	8.6	16.7	9.2	6.9	Zero	20.0	10.8	8.3	
	Aa	ABab	Bb	Aa	Bb	Bc	Light	16.7	9.2	7.5	SED=2.36
							Heavy	13.3	7.5	5.0	
15	12.5	9.4	7.2	15.6	8.9	4.7	Zero	18.3	11.7	7.5	
	Aa	Bb	Bc	Aa	Bb	Cc	Light	15.8	9.2	3.3	SED=1.80
							Heavy	12.5	5.8	3.3	
21	14.2	6.4	4.7	12.2	7.2	5.8	Zero	18.3	12.5	11.7	
	Aa	Bb	Bb	Aa	Bb	Bb	Light	10.8	5.0	3.3	SED=2.75
							Heavy	7.5	4.2	2.5	

Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case, $P<0.05$).
SED=Standard error of all interactive differences.

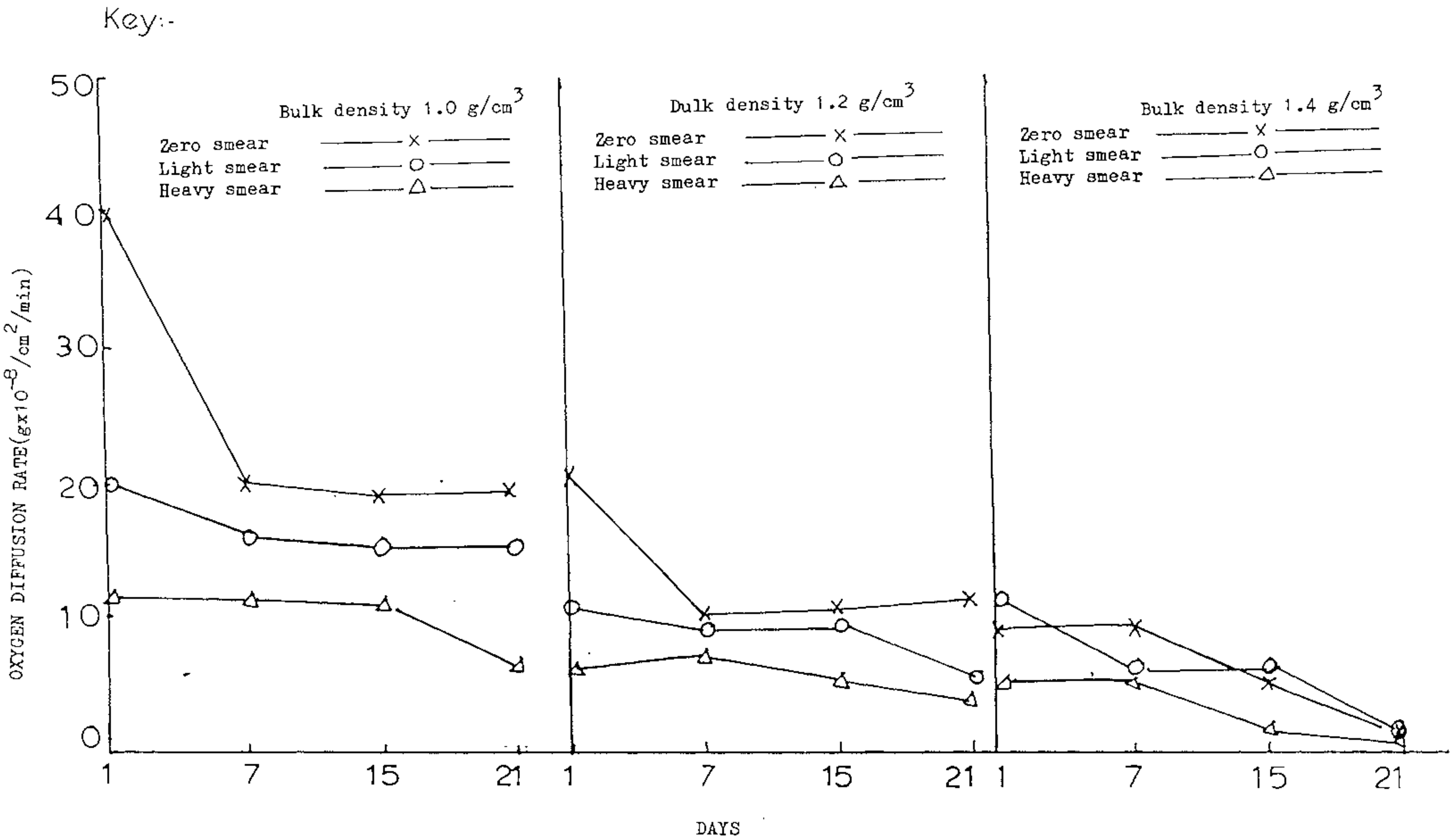


Figure 51: Effects of soil compaction levels and smearing intensities on changes in oxygen diffusion rate (ODR) with time under simulated rain conditions.

The interactions between smear intensities and contrasting soil bulk density levels (Table 46) showed that on most of the recording days the combinations of "zero" or "light" smear and soil bulk density 1.0 g/cm^3 maintained the highest values of ODR regime of all treatment combinations.

Figure 51 shows the changes in ODR values with time for each smear and bulk density level. The curves illustrate that under "zero" smear conditions with a soil bulk density of 1.0 g/cm^3 and 1.2 g/cm^3 there was a rapid reduction in ODR values between days 1 and 7, but thereafter the ODR values remained almost constant. At a soil bulk density level of 1.4 g/cm^3, the ODR values in the "zero" smear treatment remained constant at first (days 1-7) but thereafter declined steadily. The "heavy" smear with all soil bulk density levels appeared to behave in much the same manner as the "zero" smear with a bulk density of 1.4 g/cm^3. The "light" smear appeared to be intermediate, behaving in a similar manner to the "zero" smear (but to a lesser extent) in bulk densities of 1.0 g/cm^3 and 1.2 g/cm^3, but in a manner not related to either the "heavy" or "zero" smears at a bulk density of 1.4 g/cm^3. Perhaps of equal interest, was the clear illustration that as bulk density increased, the differences between smear intensity decreased, indicating that bulk density was the dominant parameter, at least within the ranges studied in this experiment.

Earthworm populations:

As already described, earthworm populations were counted at two depth ranges (0-60 mm and 60-200 mm) in undisturbed soil blocks.

Soil depth 0-60 mm:

Table 47 shows the effects of smear-intensity and contrasting soil bulk density levels on the earthworm populations, and the interactions between these two parameters. The Table shows a significant ($P<0.05$) effect of smear-intensity on the numbers of earthworms in the 0-60 mm depth range of the soil blocks. The "zero" (8.9) and "light" (10.1) smears were not significantly different, but together showed

Table 47: Effects of smearing intensity and soil bulk density, on earthworm populations, at different depths, under simulated rain conditions.

Depth from soil surface (mm)	Smear			Bulk density (g/cm^3)			Interactions				
	Zero	Light	Heavy	1.0	1.2	1.4	Bulk density/ Smear	1.0	1.2	1.4	
	Populations per soil volume*										
0-60	8.9	10.1	7.1	13.8	6.8	6.3	Zero	14.3	6.3	6.0	
	ABa	Aa	Bb	Aa	Bb	Bb	Light	16.0	7.0	7.3	SED=1.24
							Heavy	11.0	4.7	5.7	
60-200	10.4	11.2	10.0	11.0	10.6	10.1	Zero	10.7	9.7	11.0	
	Aa	Aa	Aa	Aa	Aa	Aa	Light	11.3	10.7	11.7	SED=1.71
							Heavy	11.0	11.3	7.7	

* Soil volumes: 0-60 mm depth = 1.54 litres.
60-200 mm depth= 3.58 litres.
Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case, $P<0.05$).
SED=Standard error of all interactive differences.

significantly higher numbers of earthworms than the "heavy" smear (7.1).

The contrasting soil bulk density conditions also had a significant ($P<0.05$) effect on the numbers of earthworms in the 0-60 mm depth range. At this depth the pots with soil at a bulk density of 1.0 g/cm^3 (13.8) showed significantly ($P<0.05$) higher numbers of earthworms than the pots with a bulk density of 1.2 g/cm^3 (6.8) and 1.4 g/cm^3 (6.3), which were themselves not significantly different ($P<0.05$).

The interactions between smear and bulk densities, showed that the low (1.0 g/cm^3) soil bulk density in the 0-60 mm zone had a greater beneficial effect on earthworm numbers than had levels of smear intensity. In this respect, this soil bulk density averaged 2.4 times more earthworms than any other level of soil bulk density at that depth. Interestingly, the highest number of earthworms recorded was with the "light" smear on a soil bulk density of 1.0 g/cm^3, but no logical explation can be seen for this. Where reduced counts of earthworms were recorded, earthworms were observed to have accumulated in the interspaces between the soil blocks and the plastic pots. In fact in the "heavy" smear and high bulk density treatments some earthworms had even dragged surface residue down into these relatively aerated gaps.

Soil depth 60-200 mm:

Table 47 also shows the effects of smear intensities and contrasting soil bulk density levels, on earthworm populations at the 60-200 mm depth range, and the interactions between these two parameters. The Table shows that there were no significant effects of smear intensities or soil bulk density levels on numbers of earthworms in the depth zone 60-200 mm of the undisturbed soil blocks. The interactions showed that the combination of "heavy" smear and soil bulk density level of 1.4 g/cm^3 resulted in the lowest numbers of earthworms of all treatment combinations.

3.7.3 Effects of soil smearing and compaction on earthworm activity and populations under decreasing soil moisture conditions (Experiment 13)

(a) Materials and methods:

The experiment was conducted using pots in a similar manner to Experiment 12 above, except that no simulated rain was created, and the pots were not watered further. Daily measurements of cumulative numbers of earthworm holes were taken for 21 days. The numbers of earthworms were counted at two depth ranges (0-60 mm and 60-200 mm), using a hand sorting technique in a similar manner to Experiment 12. No ODR measurements were taken in this experiment, because after day 5, the soil blocks in the pots became so dry that it was difficult to push the electrodes into the soil to a depth of 40 mm.

(b) Results and discussion:

Cumulative numbers of earthworm holes:

Table 48 shows the effects of intensities of smears and soil bulk densities, on cumulative numbers of earthworm holes, and the interactions between these two parameters. Unlike the continuously wet conditions, it appears from the Table that on day 1 there were very few earthworm holes, and statistically, the effects of smear intensities and soil bulk densities were not significantly different ($P<0.05$). However, by day 7, the effects of smear intensities on the numbers of earthworm holes were highly significant ($P<0.01$). The "zero" smear showed a significantly larger number of earthworm holes (7.4) than the "light" smear (4.6) and "heavy" smear (3.9), which were themselves not significantly ($P<0.05$) different.

Similarly, with soil bulk density levels, there were no significant ($P<0.05$) differences on day 1. On day 7, the soil bulk density of 1.4 g/cm^3 showed a significantly ($P<0.01$) lower number of earthworm holes

Table 48: Effects of smearing intensity and soil bulk density, on cumulative numbers of earthworm holes, under decreasing soil moisture conditions.

Days	Smear			Bulk density (g/cm^3)			Interactions				
	Zero	Light	Heavy	1.0	1.2	1.4	Bulk density/ Smear	1.0	1.2	1.4	
		Holes per pot*									
1	1.6	1.0	0.0	1.1	0.8	1.4	Zero	1.7	1.3	1.7	
	Aa	Aa	Aa	Aa	Aa	Aa	Light	1.0	0.3	1.7	SED=0.57
							Heavy	0.7	0.7	1.0	
7	7.4	4.6	3.9	6.4	5.4	4.0	Zero	9.0	8.7	4.7	
	Aa	Bb	Bb	Aa	Aa	Bb	Light	6.3	4.0	3.3	SED=1.03
							Heavy	4.0	3.7	4.0	

* Pot surface area = 0.0256 m^2
Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case, $P<0.05$).
SED=Standard error of all interactive differences.

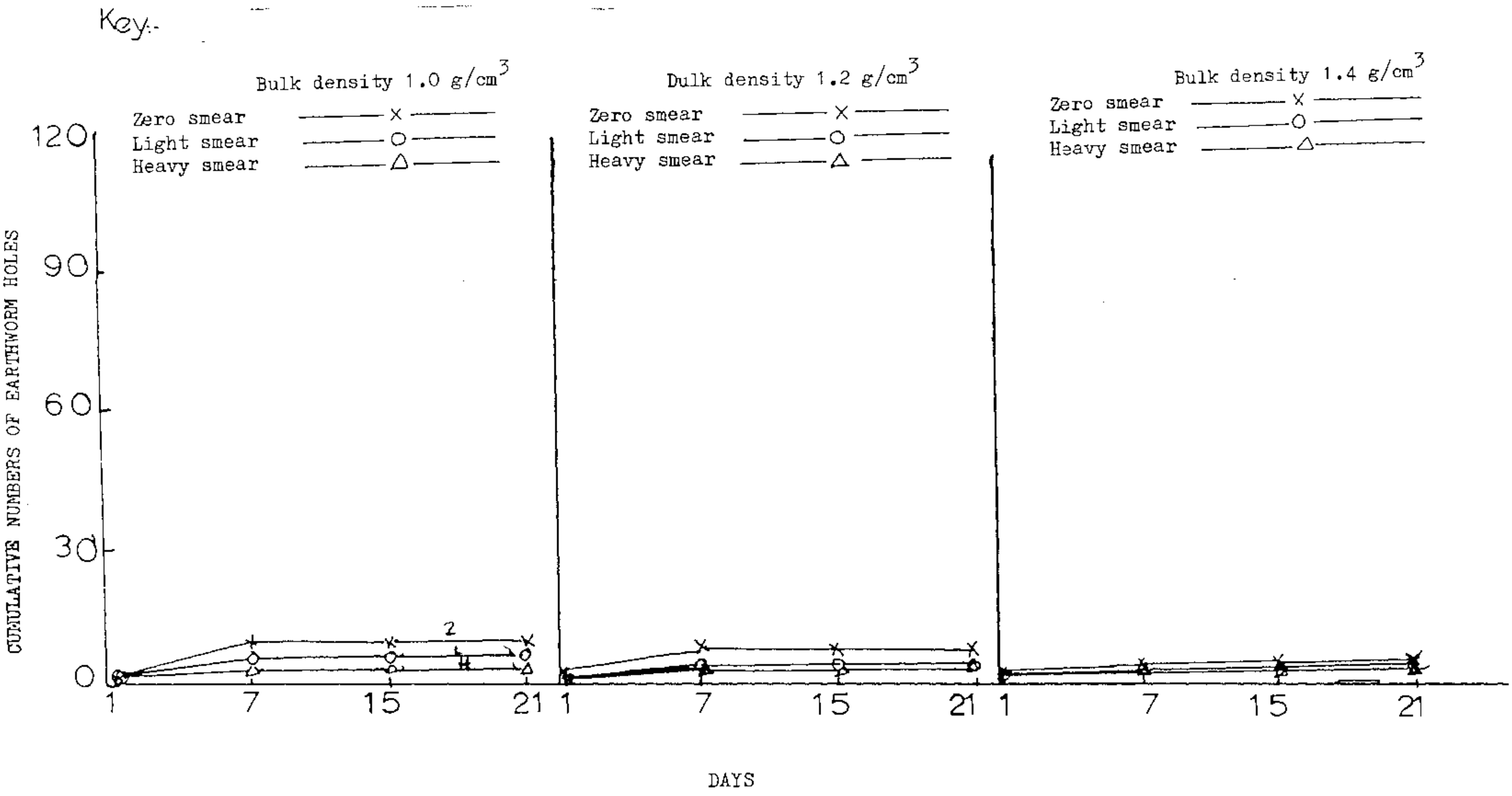


Figure 52: Effects of soil compaction levels and smearing intensities, on **cumulative** numbers of earthworm holes under continuously drying soil conditions.

(4.0), than soil bulk density levels of 1.0 g/cm^3 (6.4) and 1.2 g/cm^3 (5.4), which were not significantly different.

The interactions between smear intensities and soil bulk density levels showed only that on day 1 the "light" smear with a soil bulk density of 1.2 g/cm^3 yielded fewer earthworm holes than most of the other treatment combinations. This apparent insensitivity of earthworms to levels of smear and soil bulk density in the drier soil on day 1 contrasted with the data presented above for the wetter soil. On day 7 the "zero" smear with soil bulk density 1.0 and 1.2 g/cm^3 and the "light" smear with soil bulk density 1.0 g/cm^3 clearly promoted the highest numbers of earthworm holes.

Figure 52 shows the effects of soil compaction and smear intensities on the change of cumulative numbers of earthworm holes with time. In contrast to the wet conditions, the curves illustrate both the small increases in the cumulative numbers of earthworm holes with time (days 1-7) and the small differences between treatments. The curves also illustrate no additional earthworm activity between days 7-21 in all treatments under continuously drying soil conditions.

Earthworm Populations:

As with Experiment 12, earthworm populations were counted at two depth ranges (0-60 mm and 60-200 mm) of the undisturbed soil blocks under the continuously drying soil conditions.

Depth range 0-60 mm:

Table 49 shows the effects of smear intensity and soil bulk density levels on earthworm populations at 0-60 mm, together with the interactions between smear and bulk density. In contrast to the wet soil conditions, the numbers of earthworms at the depth range 0-60 mm were very small and there were no significant ($P<0.05$) effects of smear intensities or soil bulk density levels on earthworm populations at this depth.

Table 49: Effects of smearing intensity and soil bulk density, on earthworm populations, under decreasing soil moisture conditions.

Depth from soil surface (mm)	Smear			Bulk density (g/cm^3)			Interactions				
	Zero	Light	Heavy	1.0	1.2	1.4	Bulk density/ Smear	1.0	1.2	1.4	
				Populations per soil volume*							
0-60	1.9	2.0	1.7	2.2	1.6	1.8	Zero	2.3	1.3	2.0	
	Aa	Aa	Aa	Aa	Aa	Aa	Light	2.0	2.0	2.0	SED=0.55
							Heavy	2.3	1.3	1.3	
60-200	9.2	7.3	7.1	8.6	8.0	7.1	Zero	10.7	8.7	8.3	
	Aa	Ab	Ab	Aa	Aa	Aa	Light	7.3	7.7	7.0	SED=1.33
							Heavy	7.7	7.7	6.0	

* Soil volumes: 0-60 mm depth = 1.54 litres.
60-200 mm depth= 3.58 litres.
Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case, $P<0.05$).
SED=Standard error of all interactive differences.

Depth range 60-200 mm:

Table 49 also lists the effects of smear intensities and soil bulk density levels on earthworm populations at 60-200 mm, and the interactions between these two parameters. It appears from the Table, that "zero" smear resulted in a slightly, but significantly ($P<0.05$) larger number of earthworms (9.2) than either the "light" (7.3) or "heavy" (7.1) smears, which were themselves not significantly different. The soil bulk density levels had no significant effects on earthworm polpulations at this depth.

The interactions showed that the "zero" smear with soil bulk density 1.0 g/cm^3 promoted more earthworms than any other treatment except "zero" smear with soil bulk density 1.0 and 1.4 g/cm^3.

Under continuously drying soil conditions the depth range of 60-200 mm was observed to contain more soil moisture than the depth range of 0-60 mm. Perhaps these higher soil moisture levels might have attracted earthworms to the lower part of the undisturbed soil block. However, the earthworms in this portion of the soil were observed to be less active compared to the continuously wet soil conditions previously examined.

3.7.4 Earthworm behaviour when confronted by a smear (Experiment 14)

(a) Materials and methods:

Six holes of 120 mm diameter and 100 mm depth were made in a block of undisturbed Tokomaru silt-loam soil (at 27% d.b.soil moisture content) using a corer of the same size. The base and one half of the hole wall were given a "light" smear by wiping twice with the back of a spatula. Any possible smearing on the other half of the holes (which might have been caused as the holes were cut) was destroyed by light rubbing with a tooth brush. Ten earthworms (of mixed species) were placed in each hole.

Close observations of the movements of the earthworms were made. Photographs of the activity and movement of the earthworms were taken at one minute intervals.

(b) Results and discussion:

Figures 53 (a-d) are a series of photographs illustrating the continuous activity and movement of earthworms at the soil surfaces. During minute one, all earthworms circled at the bases of the holes. During minute 2, they all seemed to move towards the "zero" smear soil surface. During minutes 4 and 5 almost all earthworms had disappeared through the "zero" smear soil surface. Surprisingly, none of the earthworms seemed to make their way into the soil through the base or wall of the hole with the "light" smear. Perhaps this may support the suggestion that earthworms may follow the path of least resistance (J. Springett, pers comm, 1983).

This experiment, together with the previous two experiments also suggested that perhaps the response of earthworms to a smeared soil surface was similar, regardless of whether they approached the smear from within the soil or from outside the soil surface.

3.7.5 <u>Discussion of Experiments 12, 13 and 14</u>:

The results of experiments 12, 13 and 14 clearly demonstrate the significant effects on earthworm activity (as reflected by cumulative numbers of earthworm holes) of contrasting soil bulk densities and surface smear intensities. The "heavy" smear and high soil bulk density (1.4 g/cm^3) were clearly detrimental to earthworm activity, with the soil bulk density appearing to have the stronger influence in a wet soil.

These effects of soil compaction levels and smear intensities on earthworm activity, were further confirmed by the fact that the combination of low soil bulk density (1.0 g/cm^3) and "zero" smear gave the highest maximum cumulative numbers of earthworm holes. This number was six times greater than the least active treatment.

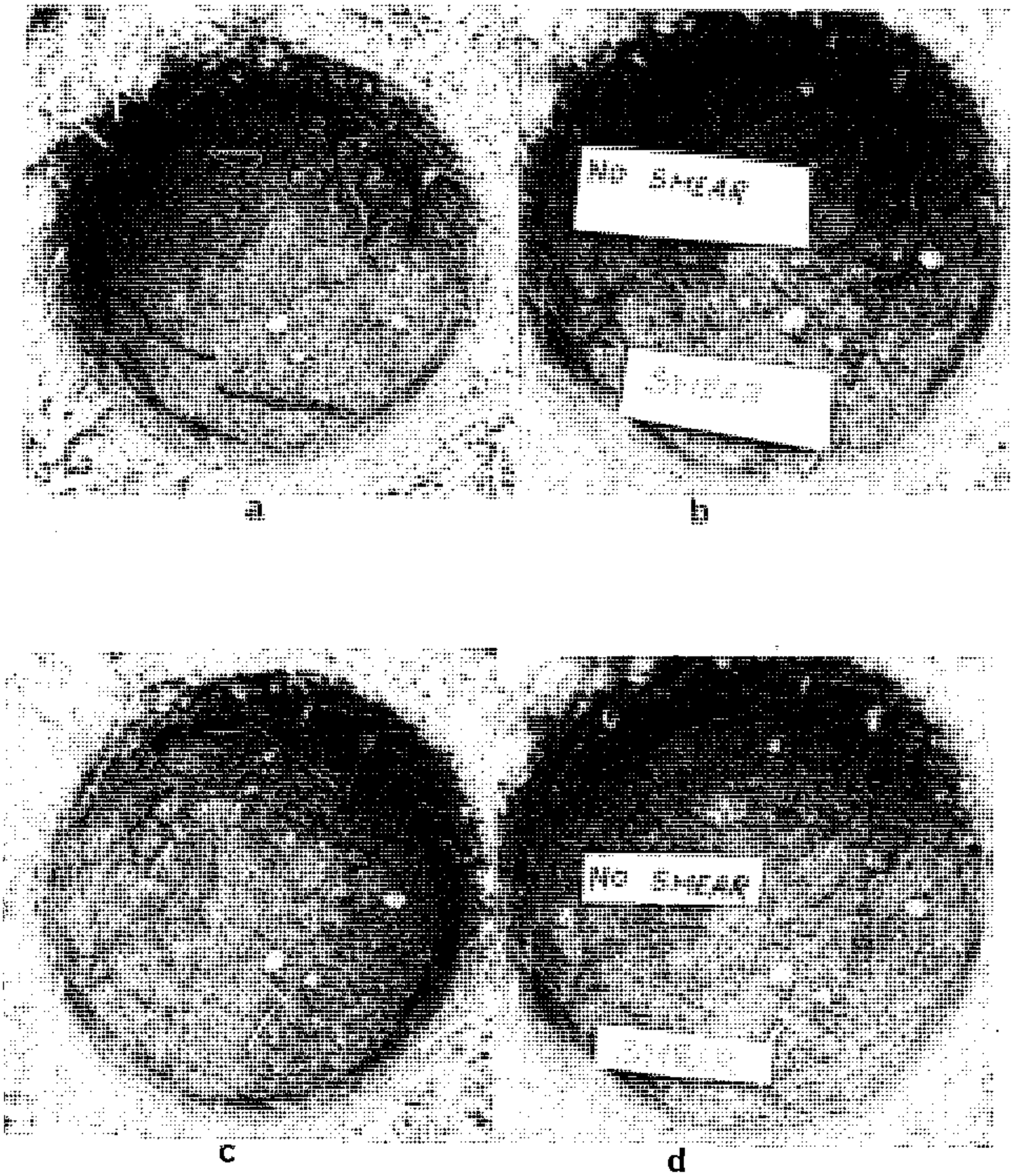


Figure 53 (a,b,c,d): Effects of smearing on movement and activity of earthworms.

Note earthworms moved towards the soil surface without smear and eventually penetrated this area.

(a) = After 2 minutes.
(b) = After 3 minutes.
(c) = After 4 minutes.
(d) = After 5 minutes.

Between days 15 and 21 earthworm activity appeared to be stopping in the "light" and "heavy" smear conditions at soil bulk density levels of 1.4 g/cm^3. Similarly, in the medium soil bulk density level (1.2 g/cm^3) the cumulative numbers of earthworm holes appeared to be constant across all smear intensities during this time.

The earthworm activity in the higher level of soil bulk density (1.4 g/cm^3) appeared to be stopping after day 7. By contrast, under the "zero" smear and/or low soil bulk density (1.0 g/cm^3) a consistent increase in the cumulative numbers of earthworm holes was observed during the entire experimental period (days 1-21). This suggested that higher levels of soil bulk density and/or intensive surface smears might be detrimental to earthworm activity, especially with time. Conversely, earthworm activity might be promoted and increased under a "zero" smear, and increased under a "zero" smear and low soil bulk density (1.0 g/cm^3) regime.

These results paralleled earlier results of earthworm activity measured in terms of area-index around the surface of grooves created by direct drilling openers (Section 3.6). In those experiments the triple disc opener grooves were noted to have been associated with a high soil bulk density and intensity of internal smear, compared to the grooves of any other opener types. This had resulted in a low number of earthworms and level of earthworm activity around the groove profile, compared to the grooves of other opener types under both no-residue and residue conditions.

It seems clear, therefore, that at least some of the mechanisms by which earthworms are either encouraged or discouraged from being active around (and even in) direct drilled grooves, are localised soil bulk density and in-groove smearing, especially the former.

The ODR data confirmed the direct effects of smear and soil compaction. The lower smear intensities and soil bulk density levels resulted in the highest ODR regimes. Perhaps these ODR values might be attributed to the high earthworm activity under "zero" smear and low levels of soil bulk density, although equally well, the reverse effect may be the case (i.e. the earthworms were more active in the high ODR zones). These experiments have not distinguished clearly between these two possibilities.

The results of these experiments also support the importance of the observations made in previous experiments of low ODR regimes around the groove of the triple disc opener, compared to the ODR regimes around the grooves of most other opener types. Many authors had reported a relationship between high soil bulk densities and reduced ODR values (Bertrand and Kohnke, 1957; Taylor, 1949; Raney, 1949). An other author had noted that factors, such as soil moisture content and the shape of the soil particles might be important (Taylor, loc.cit).

J. Springett (pers.comm., 1983) considered that earthworms might follow the path of lowest resistance. This might be supported by the fact that in the soils of depth range of 0-60 mm, the numbers of earthworms in the lower bulk density (1.0 g/cm^3) were at least twice those found in the soils of higher bulk density levels of 1.2 g/cm^3 and 1.4 g/cm^3. Furthermore, Experiment 14 showed that when earthworms were placed on a soil surface they were equally sensitive to smearing and as a result, made their way into the soil through a surface without smearing.

At a soil depth of 0-60 mm, heavy surface smearing also had a lowering effect on numbers of earthworms, compared to "zero" and "light" smear treatments. By contrast, in the 60-200 mm depth zone, numbers of earthworms were relatively insensitive to surface smearing and soil bulk density levels. Thus the numbers of earthworms around the groove profile of the triple disc opener could have been affected by smearing, whereas at deeper depths any smearing effect of such an opener would be expected to be less pronounced on earthworm numbers and activity.

Figure 54 shows the effects of soil bulk density levels on earthworm activity in the vertical section of the undisturbed soil blocks under continuously wet conditions. The Figure shows clearly a large number of earthworm channels in the soil block where the soil bulk density was 1.0 g/cm^3 (right hand side), whereas with a soil bulk density level of 1.4 g/cm^3 (left hand side) the earthworm activity in the undisturbed soil block appears to be much reduced, especially near the top of the profile.

Under dry soil conditions, earthworm activity was clearly reduced to a minimum level. After day 7 earthworm activity appeared to be stopping

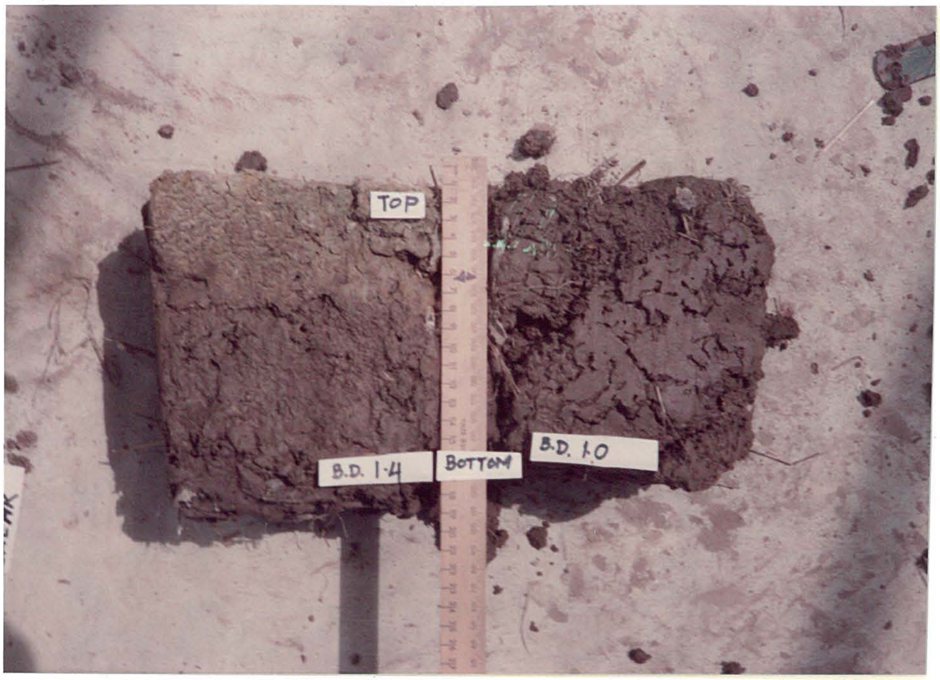


Figure 54: Effects of soil bulk density levels on earthworm channels. Note large numbers of earthworm channels in the soil with bulk density 1.0 g/cm^3 (right), and reduced earthworm activity (particularly near the top) at soil bulk density 1.4 g/cm^3 (left)

Figure 55: Effects of continuously wetting (left) and drying (right) soil on earthworm activity with a bulk density level of 1.0 g/cm^3. Note reduced numbers of earthworm holes under drying conditions.

compared to wet soil conditions where it continued. It was therefore, difficult to see any significant effect of smear or soil compaction on earthworm activity and earthworm populations in such soils, particularly in the otherwise sensitive zone of 0-60 mm.

Figure 55 shows the numbers of earthworm holes on the soil surface under continuously wetting and drying soil conditions (represented by colour pin-heads), with a soil bulk density level of 1.0 g/cm^3. There appears to be a larger number of earthworm holes under the continuously wetting soil conditions (left hand side) compared with continuously drying soil conditions (right hand side).

3.8 EFFECTS OF EARTHWORMS ON WATER INFILTRATION RATE AROUND THE PROFILES OF DIRECT DRILLED GROOVES

3.8.1 Introduction:

In earlier experiments it was observed that under simulated rain conditions the soil surface, in the absence of earthworms, had the appearance of a slurry. In some of the replicates, gravimetric soil moisture contents at a depth of 140 mm were lower than those in the top layers. It was thought possible that this was due to low infiltration rates in these conditions (J. Springett, pers.comm, 1983). The absence of earthworms may also have caused the low ODR values recorded, which in turn could have been expected to adversely affect seed germination and seedling growth.

Experiments 2, 3 and 8 indicated that under surface residue conditions the number of earthworms and their activity was greater than under no-residue conditions. It was also shown that the soil moisture content (% d.b.) around the groove profiles under surface residue conditions was slightly but significantly, lower than around the same groove profiles under no-residue conditions. It was thought that this might also have been due to differences in infiltration rates under contrasting surface residue conditions, and that these differences might have occurred because of the differences in numbers of earthworms and their activity.

It has already been seen in Section 3.3 (Pilot Experiment 4) that most of the earthworm species present were active on the top 100 mm of soil. It is possible that this might have affected water infiltration rates. However, it was also possible that the geometry of the grooves might have partially affected infiltration around the groove profiles. It was therefore decided to measure infiltration rates around the groove profiles and to do this at two infiltrometer depths (100 and 140 mm from the soil surface).

Three field experiments were conducted. The objectives of these were:

Experiment 15:

Determination of water infiltration rates into the groove profiles of five opener types and undisturbed soil in the presence of earthworms under no-residue conditions.

Experiment 16:

Determination of water infiltration rates into the groove profiles of five opener types and undisturbed soil in the absence of earthworms under no-residue conditions.

Experiment 17:

Determination of water infiltration rates into the groove profiles of five opener types and undisturbed soil in the presence of earthworms under crop residue conditions.

3.8.2 Materials and methods:

(a) Design of a rectangular infiltrometer:

Different types of infiltrometers have been used by workers to determine water infiltration rates into soil. Each type of infiltrometer has been considered suitable under specific conditions. Cylindrical ring-type infiltrometers have been the most commonly used because of their simplicity (Scotter et al, 1982). Earlier experiments in this study have shown that the critical zone of influence (in terms of changing ODR values, and numbers and activity of earthworms) was approximately 60 mm distance either side from the centre of the groove. Therefore, a rectangular infiltrometer of 120 mm width x 200 mm length x 300 mm depth was made of 3 mm steel plate. The outer edges on one side of the infiltrometers were sharpened to ease entry into the soil. Twenty four such infiltrometers were made. Figure 56 illustrates the design of the rectangular infiltrometer.

(b) Experimental design:

The experimental design involved main treatments of five true opener types and one undisturbed soil surface treatment, in a completely randomised block design with two replicates. This design was common to the three experiments. In the experimental field of Tokomaru silt-loam soil, 3 blocks of 7x10 m^2 each were marked out for each experiment. For the no earthworm/no-residue experiment (16) the plots were sprayed with herbicides (glyphosate at the rate 5.6 l/ha and dicamba at the rate of 1.5 l/ha), mown and then sprayed with carbaryl at the rate of 2 kg/ha a.i. to kill the earthworms as described in Section 3.3. For the earthworm/no-residue experiment (15) the blocks were sprayed with herbicide and mown but remained untreated with carbaryl so that the natural earthworm populations remained. For the earthworm/residue experiment (17) the blocks were treated as for experiment (15) except that surface residue was left in place as a result of spraying 3 weeks previously (as described in Section 3.2).

(c) Opener types:selection:

Five designs of openers were used on a mobile field rig, to create grooves. These were winged, triple disc, hoe, power-till and punch planter openers, together with an undisturbed soil treatment (with and without surface residue). No seed was sown in any treatment.

(d) Procedure:

The experiments were initiated at initial soil moisture contents of 23.3% (d.b) in no-residue and 27.0% (d.b) in crop residue conditions. Water infiltration rates into the groove profiles were measured 24 hours after the drilling operation. It was assumed that earthworm activity which might have been disturbed around the groove profiles during

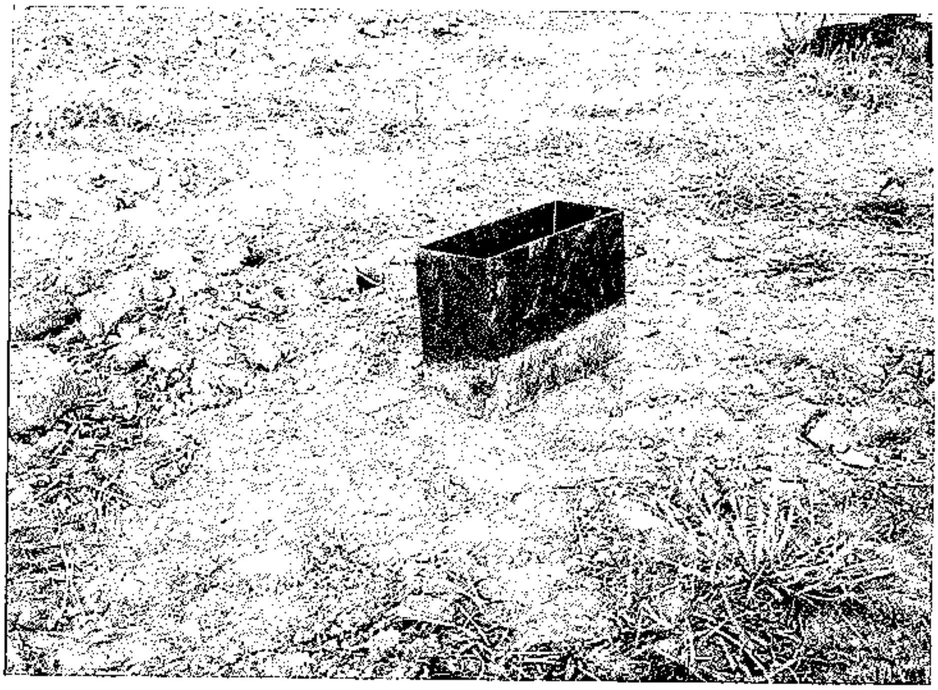


Figure 56: A rectangular infiltrometer used for measuring infiltration rate around the groove profiles created by direct drilling openers.

drilling would by then have resumed.

Rectangular infiltrometers were pushed into the soil with gentle blows from a wooden hammer. Two depths of measurement, 100 mm and 140 mm from the soil surface, were used. Both of the following procedures were adopted in all three experiments.

1. The infiltrometers were pushed into the soil, centered on the groove, to a depth of 100 mm from the soil surface. A graduated marker was placed inside each infiltrometer to show the initial and final height of water, in millimeters. Each infiltrometer was filled with water to a height of 70 mm above the soil surface and the infiltration rate was recorded at 20 minutes intervals for 2 hours.

2. Infiltrometers were pushed into the soil, centered on the groove profile, to a total depth of 140 mm fom the soil surface and infiltration rate was measured as described above. Care was taken to place the infiltrometers at least one metre apart on a given drilled groove.

3.8.3 Results and discussion:

(a) Infiltration rate in the presence of earthworms and absence of surface residue (Experiment 15)

Infiltrometer depth 100 mm:

Table 50 shows the effects of opener types and the undisturbed soil surface on water infiltration rates and cumulative infiltration around the groove profiles to a depth of 100 mm in the presence of earthworms and absence of surface residue. From the Table, there appeared to be a significant ($P< 0.05$) effect of opener types on water infiltration rate during the first 20 minutes. The grooves of the winged opener showed a significantly higher infiltration rate (195.0 mm/hr) compared to the grooves of all other openers and bare soil (mean 90.0 mm/hr). This relative difference persisted during measurements at 40,60,80,100 and 120 minutes, although the rate of infiltration decreased during this time.

Table 50: Effects of direct drilling opener types on infiltration rates and cumulative infiltration around the groove profiles, in the presence of earthworms and absence of surface residue.

Openers/ Time (min)	Infiltrometer depth = 100 mm						Infiltrometer depth = 140 mm					
	Winged	Triple disc	Hoe	Power-till	Punch planter	Bare soil	Winged	Triple disc	Hoe	Power-till	Punch planter	Bare soil
	Infiltration rate (mm/hr)											
20	195.0 Aa	75.0 Bb	105.0 Bb	82.5 Bb	82.5 Bb	105.0 Bb	180.0 Aa	82.5 Ab	82.5 Ab	97.5 Ab	97.5 Ab	112.5 Ab
40	165.0 Aa	78.0 Bb	82.5 Bb	75.0 Bb	75.0 Bb	82.5 Bb	112.5 Aa	60.0 Ac	97.5 Aab	75.0 Abc	75.0 Abc	82.5 Aabc
60	127.0 Aa	67.5 Bb	75.0 Bb	52.5 Bb	67.5 Bb	67.5 Bb	82.5 Aa	52.5 Aa	60.0 Aa	67.5 Aa	55.5 Aa	64.5 Aa
80	123 Aa	64.5 Bb	67.5 Bb	48.0 Bb	60.0 Bb	63.0 Bb	60.0 Aa	37.5 Aa	48.0 Aa	52.5 Aa	40.5 Aa	52.5 Aa
100	117.0 Aa	52.5 Bb	60.0 Bb	46.5 Bb	52.5 Bb	48.0 Bb	52.5 Aa	37.5 Aa	40.5 Aa	45.0 Aa	37.5 Aa	45.0 Aa
120	106.5 Aa	54.0 Bb	45.0 Bc	48.0 Bbc	51.0 Bbc	45.0 Bc	37.5 Aa	31.5 Aa	37.5 Aa	37.5 Aa	34.5 Aa	37.5 Aa
Cumulative infiltration (mm)	834 Aa	392 Bb	435 Bb	353 Bb	389 Bb	411 Bb	525 Aa	302 Ab	336 Ab	375 Aab	341 Ab	395 Aab

Unlike letters in a row denote significant differences (upper case, P<0.01; Lower case, P<0.05).

At 100 minutes the grooves of the winged opener had an infiltration rate of 117 mm/hr which was still significantly greater than the grooves of all other openers and bare soil, which averaged 51.9 mm/hr. After 120 minutes while the groove of the winged opener continued its highly significant superiority over all other openers, by then the triple disc opener was superior to the hoe opener and bare soil.

Not surprisingly, the grooves of the winged opener showed a significantly ($P<0.05$) higher cumulative infiltration (834 mm) than all other grooves which averaged 396 mm.

Infiltrometer depth 140 mm:

Table 50 also shows the effects of opener types and the undisturbed soil surface on water infiltration rates and cumulative infiltration around the groove profiles to a depth of 140 mm in the presence of earthworms and absence of surface residue. It appears from the Table, that during the first 20 minutes the infiltration rate of the grooves of the winged opener (180 mm/hr) was significantly ($P<0.05$) higher than the infiltration rates of the grooves created by all other openers (mean 94.5 mm/hr). These diferences remained largely unchanged at 40 minutes. However, during all subsequent time intervals (60,80,100 and 120 minutes) the infiltration rates amongst the grooves of all opener types and undisturbed soil were not significantly different ($P<0.05$).

The cumulative infiltration in the grooves of the winged opener (525 mm) was significantly ($P<0.05$) higher than the grooves of the triple disc (302 mm), hoe (336 mm), power-till (375 mm) and punch planter (341 mm) openers, but the grooves of the power-till opener were not significantly different from bare soil (395 mm). The latter two treatments were also not significantly different than the triple disc, hoe and punch planter openers.

(b) Infiltration rate in the absence of earthworms and surface residue. (Experiment 16)

Infiltrometer depth 100 mm:

Table 51 shows the effects of opener types and undisturbed/bare soil on water infiltration rates and cumulative infiltration to 100 mm in the absence of earthworms and surface residue. The Table shows that during the first 20 minutes the grooves of the winged opener showed a significantly ($P<0.05$) higher infiltration rate (48.0 mm/hr) than all other grooves. The groove of the triple disc opener (33.o mm/hr) was also superior to the undisturbed/bare soil (16.5 mm/hr). The infiltration rates in the grooves of the hoe, power-till, and punch planter openers, and undisturbed soil were not significantly different. A similar trend of infiltration rates was found after 40 minutes except that the triple disc opener was by then not significantly different from the winged opener, but these two were significantly higher than all other openers except the hoe. However, at all other time intervals (60,80,100 and 120 minutes) the infiltration rates amongst the grooves of all opener types and the undisturbed/bare soil were not significantly different.

In terms of cumulative infiltration, the grooves of the winged opener showed a significantly ($P<0.05$) higher infiltration (111.0 mm) than all other grooves and the undisturbed soil surface. The grooves of the triple disc opener (78.0 mm) were higher than all other treatments except the grooves of the power-till opener (52.0 mm). The grooves of the hoe (48.0 mm) and punch planter (48.0 mm) openers and the undisturbed/bare soil (43.5 mm) were not significantly different.

Infiltrometer depth 140 mm..

Table 51 also shows the effects of opener types and undisturbed bare soil on water infiltration rates and cumulative infiltration to 140 mm in the absence of earthworms and surface residue . From the Table, it appears that there were no significant differences in infiltration rates amongst the grooves of all opener types and undisturbed/bare soil at any

Table 51: Effects of direct drilling opener types on infiltration rates and cumulative infiltration around the groove profiles, in the absence of earthworms and surface residue.

Openers/ Time (min)	Infiltrometer depth = 100 mm						Infiltrometer depth = 140 mm					
	Winged	Triple disc	Hoe	Power-till	Punch planter	Bare soil	Winged	Triple disc	Hoe	Power-till	Punch planter	Bare soil
	Infiltration rate (mm/hr)											
20	48.0 Aa	33.0 ABb	18.0 Bbc	24.0 Bbc	21.0 Bbc	16.5 Bc	22.5 Aa	19.5 Aa	25.5 Aa	13.5 Aa	15.0 Aa	18.0 Aa
40	25.5 Aa	18.0 ABab	10.5 Bbc	9.0 Bc	7.5 Bc	7.5 Bc	10.5 Aa	12.5 Aa	10.5 Aa	10.5 Aa	7.5 Aa	13.5 Aa
60	13.5 Aa	12.0 Aa	6.0 Aa	7.5 Aa	7.5 Aa	6.0 Aa	10.5 Aa	6.0 Aa	7.0 Aa	7.5 Aa	6.0 Aa	7.5 Aa
80	10.5 Aa	6.0 Aa	4.5 Aa	4.5 Aa	4.5 Aa	6.0 Aa	10.5 Aa	4.5 Aa	7.5 Aa	7.5 Aa	4.5 Aa	6.0 Aa
100	7.5 Aa	6.0 Aa	4.5 Aa	4.5 Aa	4.5 Aa	4.5 Aa	6.5 Aa	3.0 Aa	6.0 Aa	4.5 Aa	4.5 Aa	6.0 Aa
120	6.0 Aa	3.0 Aa	4.5 Aa	3.0 Aa	3.0 Aa	3.0 Aa	6.5 Aa	3.0 Aa	6.0 Aa	4.5 Aa	3.0 Aa	3.0 Aa
Cumulative infiltration (mm)	111.0 Aa	78.0 ABb	48.0 Bc	52.0 Bbc	48.0 Bc	43.5 Bc	67.0 Aa	48.0 Aa	63.0 Aa	48.0 Aa	40.5 Aa	54.0 Aa

Unlike letters in a row denote significant differences (upper case, P<0.01; lower case, P<0.05).

of the time intervals (20,40,60,80,100 and 120 minutes). Similarly, there were no signifcant differences in cumulative infiltration amongst the grooves of all opener types and undisturbed/bare soil.

(c) Infiltration rate in the presence of earthworms and surface residue (Experiment 17)

Infiltrometer depth 100 mm:

Table 52 shows the effects of opener types and undisturbed soil on infiltration rates and cumulative infiltration to 100 mm in the presence of earthworms and crop residue. From the Table, it appears that during the first 20 minutes there were no significant differences in infiltration rates amongst the grooves of all opener types and undisturbed soil surface. However, after 40 minutes the infiltration rates in the grooves of the winged (163.5 mm/hr) and power-till (153.0 mm/hr) openers were significantly (P<0.05) higher than the infiltration rates of the grooves of the hoe (145.5 mm/hr), triple disc (96.0 mm/hr) and punch planter (99.0 mm/hr) openers, together with the undisturbed soil surface (103.5 mm/hr). The infiltration rates of the grooves of the hoe and power-till openers were not significantly different. However, at all other time intervals (60,80,100 and 120 minutes) the infiltration rates of the grooves of the winged opener were significantly higher than the grooves of all other opener types and the undisturbed soil surface. The triple disc opener showed significantly (P<0.05) the lowest infiltration rate compared to all other opener types and the undisturbed soil surface.

The cumulative infiltration in the grooves of the winged opener was significantly (P<0.05) higher (841.0 mm) than the grooves of all other opener types. The hoe (633.0 mm) and power-till opener (649.5 mm) grooves showed higher cumulative infiltrations than the undisturbed soil (546.0 mm), which itself was superior to the triple disc (419.0 mm). The punch planter opener (576.0 mm) was not significantly (P<0.05) different from the hoe and power-till opener treatments.

Table 52: Effects of direct drilling opener types on infiltration rates and cumulative infiltration around the groove profiles, in the presence of earthworms and surface residue.

Openers/ Time (min)	Infiltrometer depth = 100 mm						Infiltrometer depth = 140 mm					
	Winged	Triple disc	Hoe	Power-till	Punch planter	Bare soil	Winged	Triple disc	Hoe	Power-till	Punch planter	Bare soil
	Infiltration rate (mm/hr)											
20	190.5 Aa	174.0 Aa	166.5 Aa	169.5 Aa	156.0 Aa	163.5 Aa	169.5 Aa	133.5 ABab	160.5 Aa	105.0 ABabc	76.5 Bc	78.0 Bc
40	163.5 Aa	96.0 Bc	145.5 Ab	153.0 Aab	99.0 Bc	103.5 Bc	145.5 Aa	91.5 Cc	118.5 Bb	81.0 CDcd	70.5 Dd	64.5 De
60	156.0 Aa	63.0 Cd	111.0 Bb	114.0 Bb	96.0 BCb	79.5 Cc	112.5 Aa	48.0 Cc	69.0 Bb	60.0 Bbc	48.0 Cc	42.0 Cd
80	117.0 Aa	42.0 Cc	75.0 Bb	84.0 ABb	81.0 Bb	69.0 BCb	64.5 Aa	28.5 Bd	43.5 Bb	34.5 Bbc	30.0 Bd	31.5 Bcd
100	108.0 Aa	27.5 Cd	70.5 Bbc	64.5 Bc	75.0 Bb	66.0 Bc	64.5 Aa	24.0 Cc	36.0 Bb	25.5 BCc	25.5 BCc	22.5 Cc
120	106.5 Aa	22.5 Cc	64.5 Bb	64.5 Bb	69.0 Bb	64.0 Bb	58.5 Aa	22.5 Bb	27.0 Bb	22.5 Bb	25.5 Bb	22.5 Bb
Cumulative infiltration (mm)	841.5 Aa	419.0 Cd	633.0 Bb	649.5 Bb	576.0 Bbc	546.0 Bc	615.0 Aa	348.0 Cc	454.5 Bb	328.5 Ccd	276.0 Ccd	261.0 Cd

Unlike letters in a row denote significant differences (upper case, $P<0.01$; lower case, $P<0.05$).

Infiltrometer depth 140 mm:

Table 52 also lists the effects of opener types and the undisturbed soil surface on water infiltration rates and cumulative infiltration to 140 mm in the presence of earthworms and surface residue. It appears from the Table, that during the first 20 minutes the infiltration rates of all grooves were similar except for the punch planter and the undisturbed soil surface, which were significantly slower than all treatments except the power-till opener. Thereafter, a trend developed where the grooves of the winged opener showed consistently and significantly (P<0.05) faster infiltration than all other openers and the undisturbed soil surface. There were some inconsistent changes amongst these other treatments as the experiment progressed, but no clear trend emerged other than the superiority of the grooves of the winged opener.

Not surprisingly, the grooves of the winged opener had a significantly (P<0.05) higher cumulative infiltration (615.0 mm) followed by the grooves of the hoe opener (454.5 mm). The grooves of the triple disc (348.0 mm),power-till (328.5 mm) and punch planter (276.0 mm) openers had significantly lower cumulative infiltrations compared to all other opener types. The undisturbed soil surface had a significantly (P<0.05) lower cumulative infiltration than all but the grooves of the power-till and punch planter openers.

Figures 57 (a, b) and 58 (a, b) show the infiltration rates in the presence and absence of earthworms (in no-residue) respectively, at the two infiltrometer depths (100 and 140 mm). Similarly, Figures 59 (a, b) illustrate the infiltration rates at the same two infiltrometer depths, both in the presence of earthworms and surface residue. These curves illustrate the magnitude of differences amongst groove types and the undisturbed/bare soil in the presence of earthworms, and the relative insensitivity of opener types in the absence of earthworms. The curves also illustrate the declining infiltration rates of all treatments with time, except with the 100 mm infiltrometer depth in the absence of earthworms where the infiltration rates were very slow in all treatments.

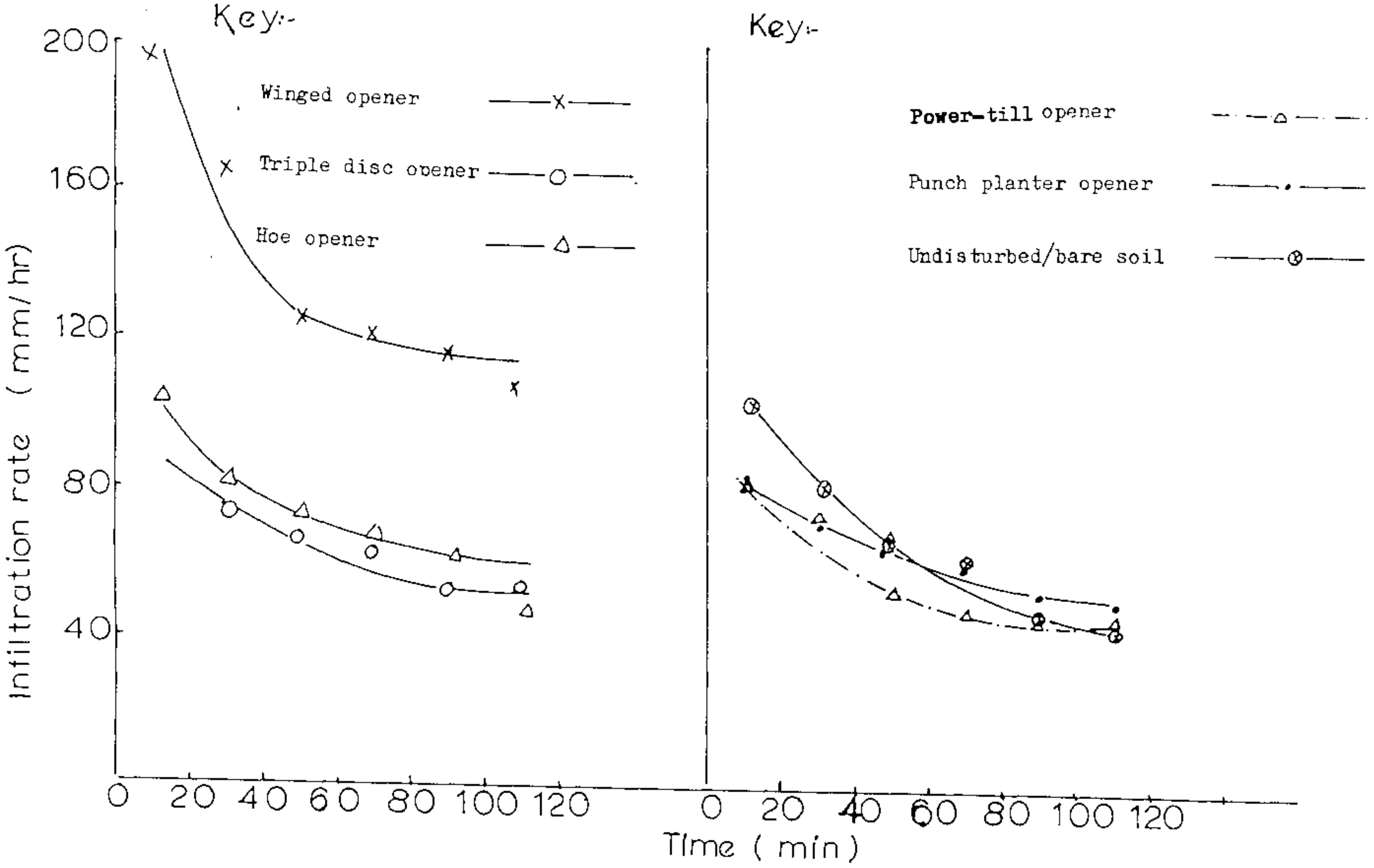


Figure 57a: Effects of direct drilling opener types and undisturbed/bare soil on infiltration rate to 60 mm, in the pressnce of earthworms and absence of crop residues.

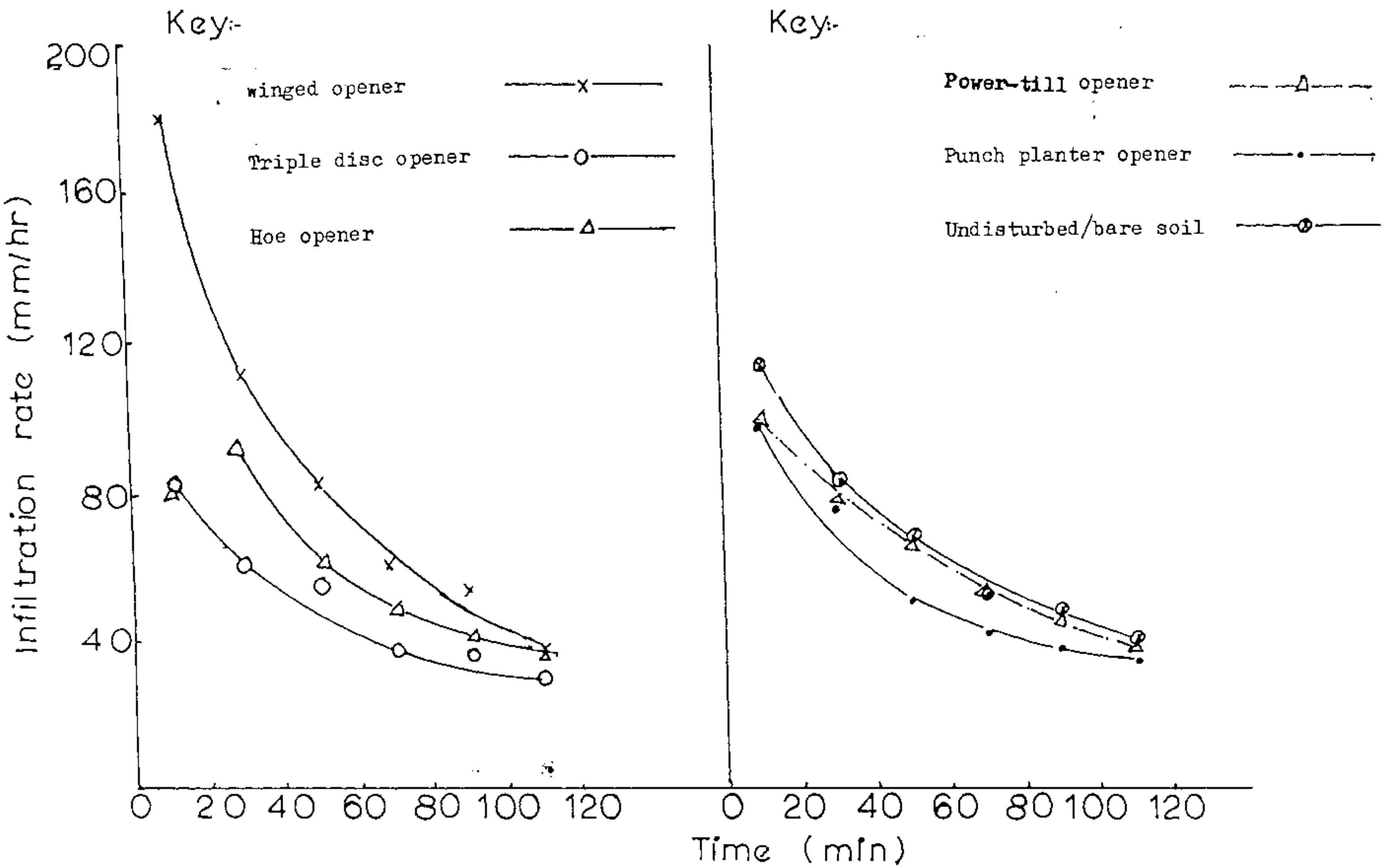


Figure 57b: Effects of direct drilling opener types and undisturbed/bare soil on infiltration rate to 10C mm, in the presence of earthworms and absence of crop residue.

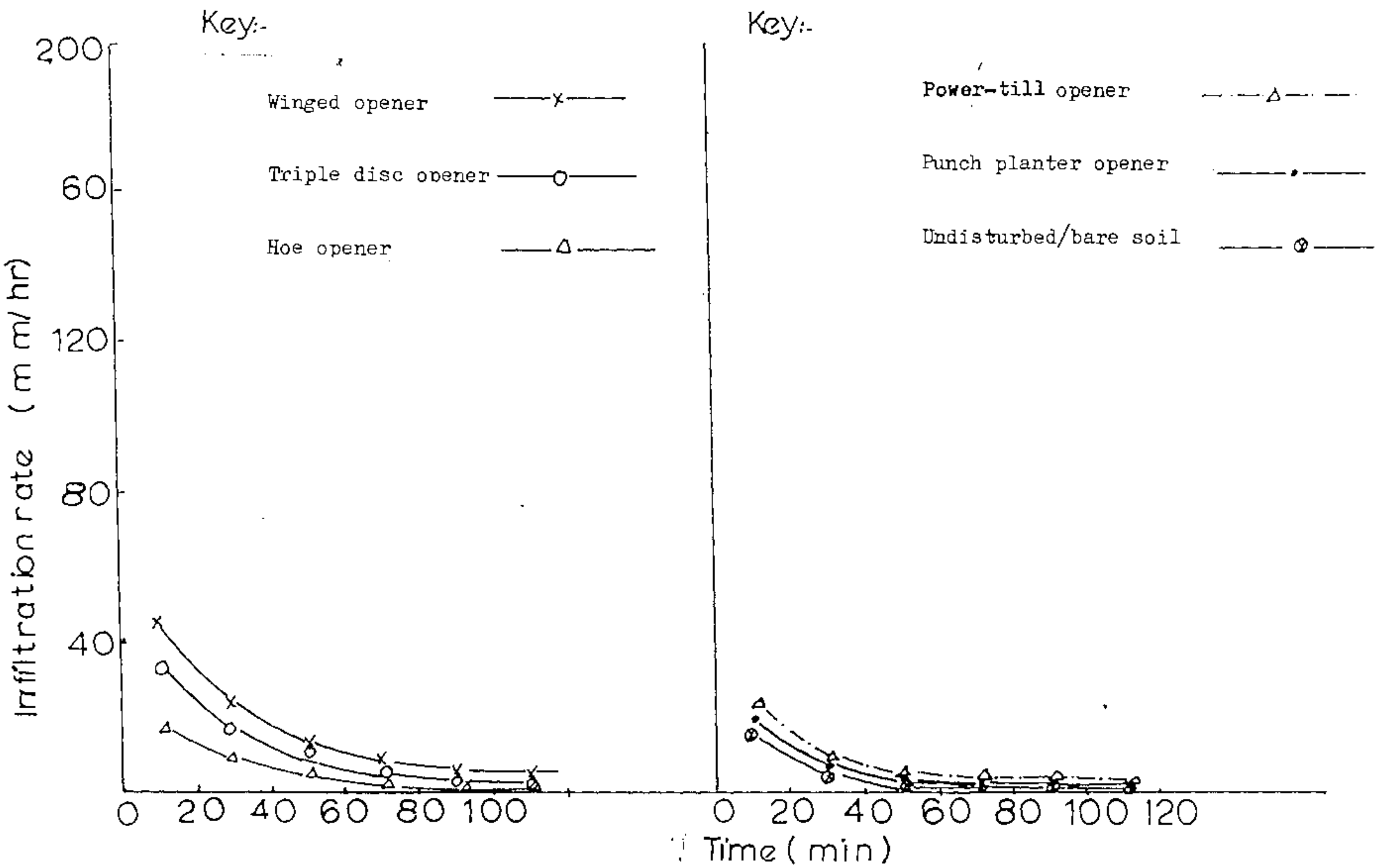


Figure 58a: Effects of direct drilling opener types and undisturbed/bare soil on infiltration rate to 60 mm, in the absence of earthworms and crop residue.

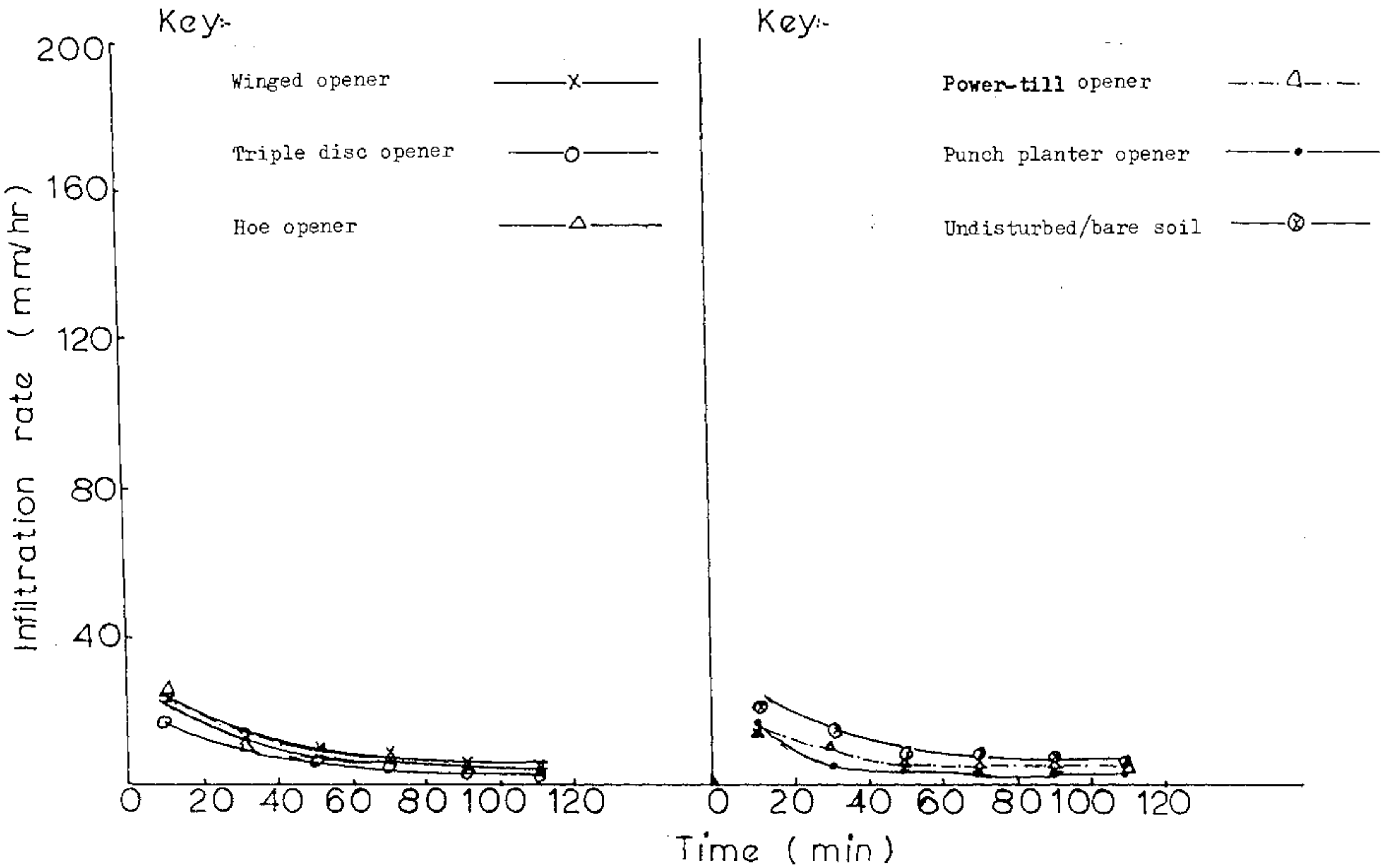


Figure 58b: Effects of direct drilling opener types and undisturbed/bare soil on infiltration rate to 100 mm, in the absence of earthworms and crop residues.

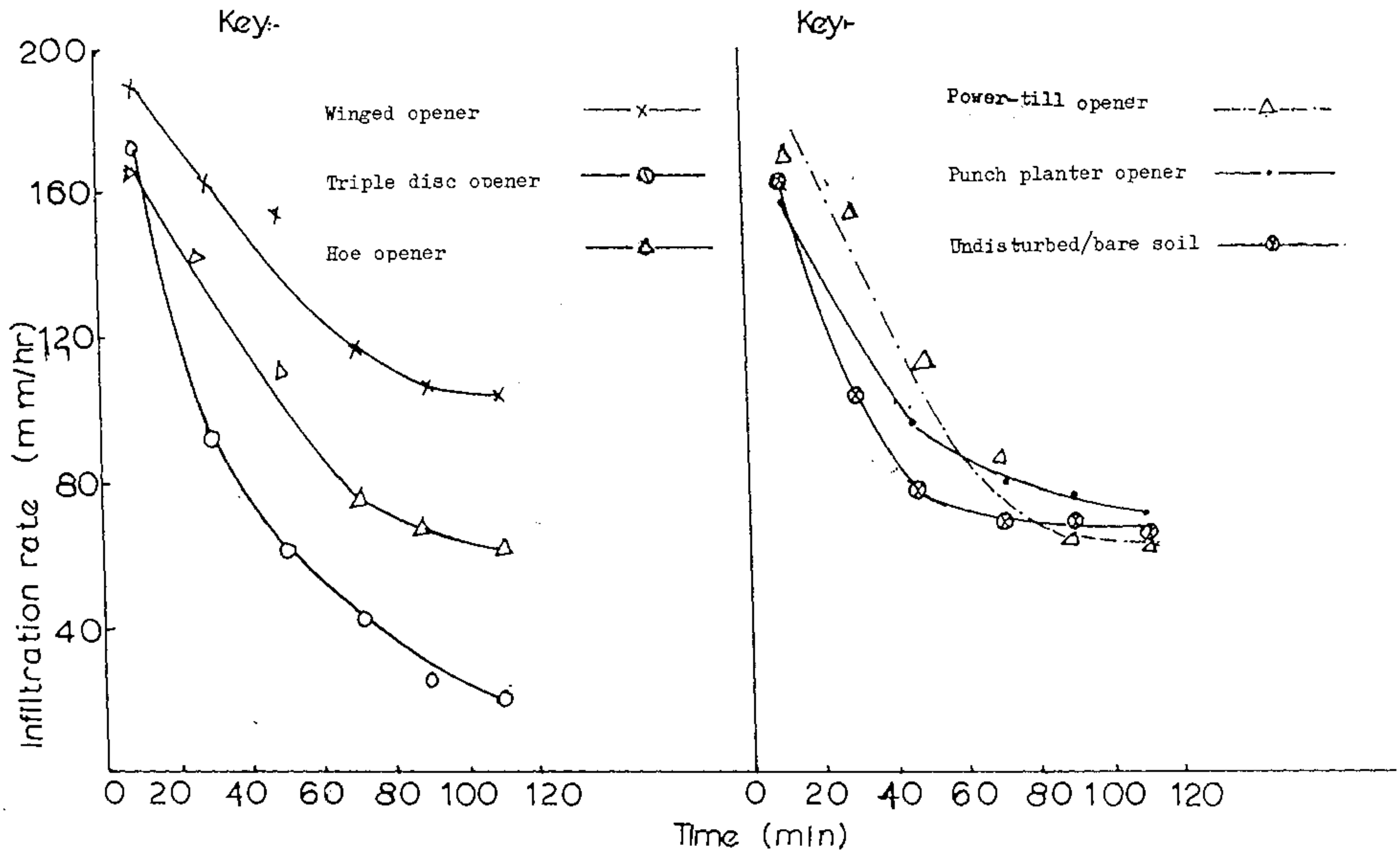


Figure 59a: Effects of direct drilling opener types and undisturbed soil on infiltration rate to 60 mm, in the presence of earthworms and crop residue .

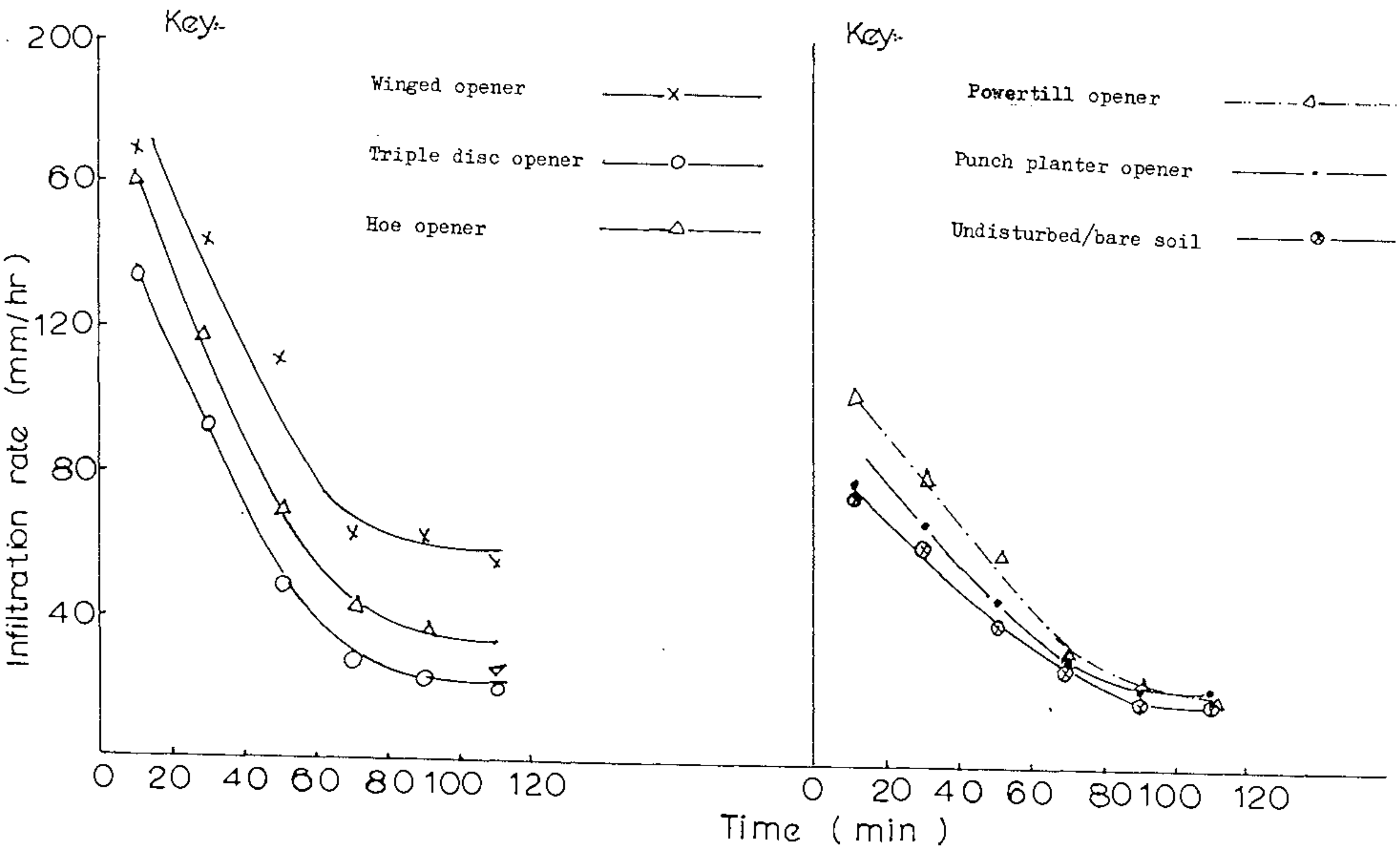


Figure 59b: Effects of direct drilling opener types and undisturbed soil on infiltration rate to 100 mm, in the presence of earthworms and crop residue .

3.8.4 Discussion of Experiments 15, 16 and 17:

The characteristics of the geometry of the drilled grooves appeared to affect infiltration rates around the groove profiles. The winged opener at both infiltrometer depths (100 and 140 mm) and in the presence of earthworms (and in both the presence and absence of surface residue) showed almost twice the cumulative infiltration of any other opener type or the undisturbed soil surface. Perhaps this might be attributable to the characteristics of the winged opener groove which loosened and shattered the soil at the sides and bases of the grooves compared to the grooves created by most other opener types and the undisturbed soil surface. For example, the triple disc grooves had a compaction and smearing effect, and in these conditions even the hoe and power-till openers created grooves which appeared to have lower soil shattering at the bases of the grooves than the grooves of the winged opener. The punch planter opener with narrow "U" shaped discrete holes (11 mm in dia) appeared to disturb the soil very little.

The performance of the grooves of the winged opener (in terms of cumulative infiltration) was 8 times higher in the presence of earthworms and residue than in the absence of earthworms and residue. Nevertheless, the winged opener grooves in the absence of earthworms and residue showed significantly higher cumulative infiltration than any other opener type or the undisturbed soil surface when the infiltrometer depth was 100 mm. This superiority disappeared with an infiltrometer depth of 140 mm, in the absence of earthworms and surface residue. As the seedling emergence performance of the groove of the winged opener was inferior to that of the power-till opener in the absence of earthworms, it would appear that the infiltration characteristics (at least as measured in these experiments and in this soil) were not clearly related to seedling emergence.

Comparisons of earthworm effects are more difficult as they represented separate, but otherwise identical experiments. As described earlier, most of the earthworm species which were identified, were active in the 100 mm top layer of soil. The results, however, might suggest a direct effect of earthworm activity on water infiltration rates around the groove profiles. The average cumulative infiltration of all opener types and the undisturbed soil surface with the 100 mm infiltrometer depth in the presence of earthworms and absence of surface residue was 24% higher than where the infiltrometer depth had been 140 mm in the same experiment. This difference might be partially attributable to the greater numbers of earthworms and their activity in the 0-100 mm depth zone compared with that in the more extended zone to 140 mm below the soil surface. On the other hand, in the experiment which included the absence of earthworms and surface residue, the difference in the average cumulative infiltration across all opener types and undisturbed soil surface between the two infiltrometer depths was small (63.5 mm for 100 mm depth, and 53.3 mm for 140 mm depth).

In comparing experiments, it seems that when earthworms and residue were present, the infiltrometer depth of 100 mm recorded approximately 9 times greater cumulative infiltration compared with when earthworms and residue were absent. The presence of earthworms alone might have accounted for a 7 fold increase in infiltration compared to the absence of earthworms at this depth. Hopp and Slater (1949) had reported 4 to 10 times higher infiltration rates with earthworms compared with no-earthworms. The results in this set of experiments might add weight to that report.

It might therefore be concluded that in the absence of earthworms the differences in the geometry of the grooves had less effect on infiltration around the groove profiles than where earthworms were present. In that situation, the geometry of the groove could be a strong determinant in influencing infiltration rates around the groove profiles.

It could also be concluded with greater certainty that the effects of opener types (and also perhaps earthworm activity) were strongest when infiltration was measured to 100 mm depth beneath the soil surface.

The results also show clearly, the beneficial effects on infiltration of the inverted "T" shaped groove created by the winged opener, especially when earthworms were present.

3.9 LIMITING FACTORS CAUSING SEEDLING EMERGENCE FAILURE WITH THE TRIPLE DISC OPENER GROOVE (Experiment 18)

3.9.1 Introduction:

In earlier experiments (2, 3, 8 and 11) the triple disc opener appeared to have performed poorly in terms of seedling emergence. In wet soils, seedling emergence from the grooves created by this opener was consistently lower than all other opener types (except the punch planter opener) under crop residue conditions, even although it was significantly improved under residue when contact between residue and seed was prevented.

It was felt that any improvements which could be made to a poorly performed opener, would help explain the mechanisms by which openers, in general, affected seedling performance. Furthermore, this particular opener was amongst the most commercially used designs, and improvements to its performance were likely to be direct of benefit to the industry.

An experiment was therefore designed to test a number of different modifications to the grooves of the triple disc opener, which might be expected to improve its ability to promote seed germination and seedling emergence.

3.9.2 Materials and methods:

The opener options were used to create 40 mm deep "V"-shaped grooves in plots in the experimental field of Tokomaru silt-loam soil, with natural levels of earthworms, and where crop residue was removed prior to drilling. The experimental design was a randomised complete block with three replicates. Soil blocks with their drilled grooves (250 mm wide x 320 mm long x 200 mm deep) were cut and extracted with a spade and placed in steel pots of the same size. The under sides of soil blocks were trimmed so that they rested flat on the bases of the pots. All four sides of these blocks were covered with molten wax using the same technique as described in Section 3.3. The soil blocks were transported to a glasshouse where they were placed in a randomised block design with three replicates of each treatment.

The treatments were as listed below:

Grooves were created using a triple disc opener (with plain front disc) in the normal manner. Any surface smearing or in-groove compaction was considered to be a characteristic of the grooves.

It had been observed that the grooves created by this version of the triple opener were smeared by the opener in the course of creation. In some of these grooves the surface-appearance of these smears was destroyed by light rubbing with a tooth brush in such a manner that the shape of the groove was not altered. It is possible that this smear-destruction technique had little more than a cosmetic effect, but it was difficult to see any other simple technique which would destroy the smear (which was of unknown thickness) without altering the geometry of the groove in some way.

In the undrilled undisturbed soil blocks "V" shaped grooves of identical geometrical shape to those created by the triple disc opener were cut by hand using a knife.

Contrasting crop residue conditions were created as described below.

The soil blocks were cleared of surface residue after spraying with 5.6 l/ha a.i. glyphosate and 1.5 l/ha a.i. dicamba. Crop residue was added to the other treatments.

The "Residue-on-top" treatment had the residue spread evenly on the soil surface.

The "Residue-in-groove" treatment was created by pushing the residue into the grooves using a spatula. Care was taken to maintain the shape of the groove during this operation.

Twenty seeds were placed in each treatment with forceps in the same manner as in earlier experiments (7, 8, 9, 10 and 11). All the undisturbed soil blocks were kept under simulated rain conditions of 20 mm a day at an intensity of 5 mm per hour. The glasshouse temperature was maintained between 15-20 ^{o}C. The experiment continued for 21 days. Seedling emergence, root/shoot weights and earthworm populations were taken after 21 days. The measurements of ODR regimes around the groove profiles were taken on days 1, 7, 15, and 21. For ODR measurements, a pattern was used of 16 points around the groove profiles, in an identical manner to earlier experiments (2, 3, 10 and 11). The holes left by the electrodes were immediately filled with slurry after the electrodes were removed.

3.9.3 Results and discussion:

(a) Seedling emergence:

Table 53 shows the effects of "V"-shaped groove types and contrasting crop residue conditions, on percentage seedling emergence and seed fate, and the interactions between these parameters. From the Table, it appears that the grooves cut by the knife promoted a significantly ($P<0.01$) higher percentage seedling emrgence (71.7%) compared with either of the grooves created by the triple disc opener, regardless of smearing or "destruction" of the same. The latter two types of grooves (which averaged 48.0% emergence) were not significantly different ($P<0.05$).

The contrasting crop residue conditions also had a highly significant ($P<0.01$) effect on seedling emergence. The "residue-in-groove" showed significantly less seedling emergence (26.1%) than the "residue-on-top" (71.1%) and "no-residue" (70.6%) conditions, which were not significantly different. Avoiding this residue condition appeared to be more important than avoiding smearing, as the overall performance with residue in the groove was half that of smearing.

There appeared to be strong interactions between groove types and contrasting crop residue conditions. Grooves cut by the hand-drawn knife with either no-residue or with the residue confined to the surface, showed the highest maximum seedling emergence. By contrast it was also

Table 53: Effects of "V" shaped groove types and crop residue conditions, on seed fate of barley, under simulated rain conditions.

Seed fate	"V" shaped groove types			Residue			Interactions				
	Knife cut	Opener created (SD#)	Opener created (S##)	NR*	RT**	RI***	Grooves/ Residue	Knife cut	Opener created (SD)	Opener created (S)	
Seedling emergence (%)	71.7	46.7	49.4	70.6	71.1	26.1	NR	93.3	53.3	66.3	
	Aa	Bb	Bb	Aa	Aa	Bb	RT	91.7	65.0	56.7	SED=7.54
							RI	30.0	21.7	26.7	
Ungerminated or dead seeds (%)	15.4	26.7	25.6	12.2	11.6	43.9	NR	1.7	20.0	15.0	
	Bb	Aa	Aa	Bb	Bb	Aa	RT	3.0	13.3	18.3	SED=4.35
							RI	41.7	46.7	43.3	
Germinated but unemerged Seedlings (%)	12.9	26.7	25.0	17.2	17.3	30.0	NR	5.0	26.7	20.0	
	Bb	Aa	Aa	Bb	Bb	Aa	RT	5.3	21.7	25.0	SED=4.66
							RI	28.3	31.7	30.0	

*NR = No surface residue present
**RT = Surface residue on top of the grooves
***RI= Surface residue pushed into the grooves
#SD = Smear destroyed
##S = Smear present
Unlike letters in a row denote significant differences (upper case, P<0.01; lower case, P<0.05).
SED=Standard error of all interactive differences.

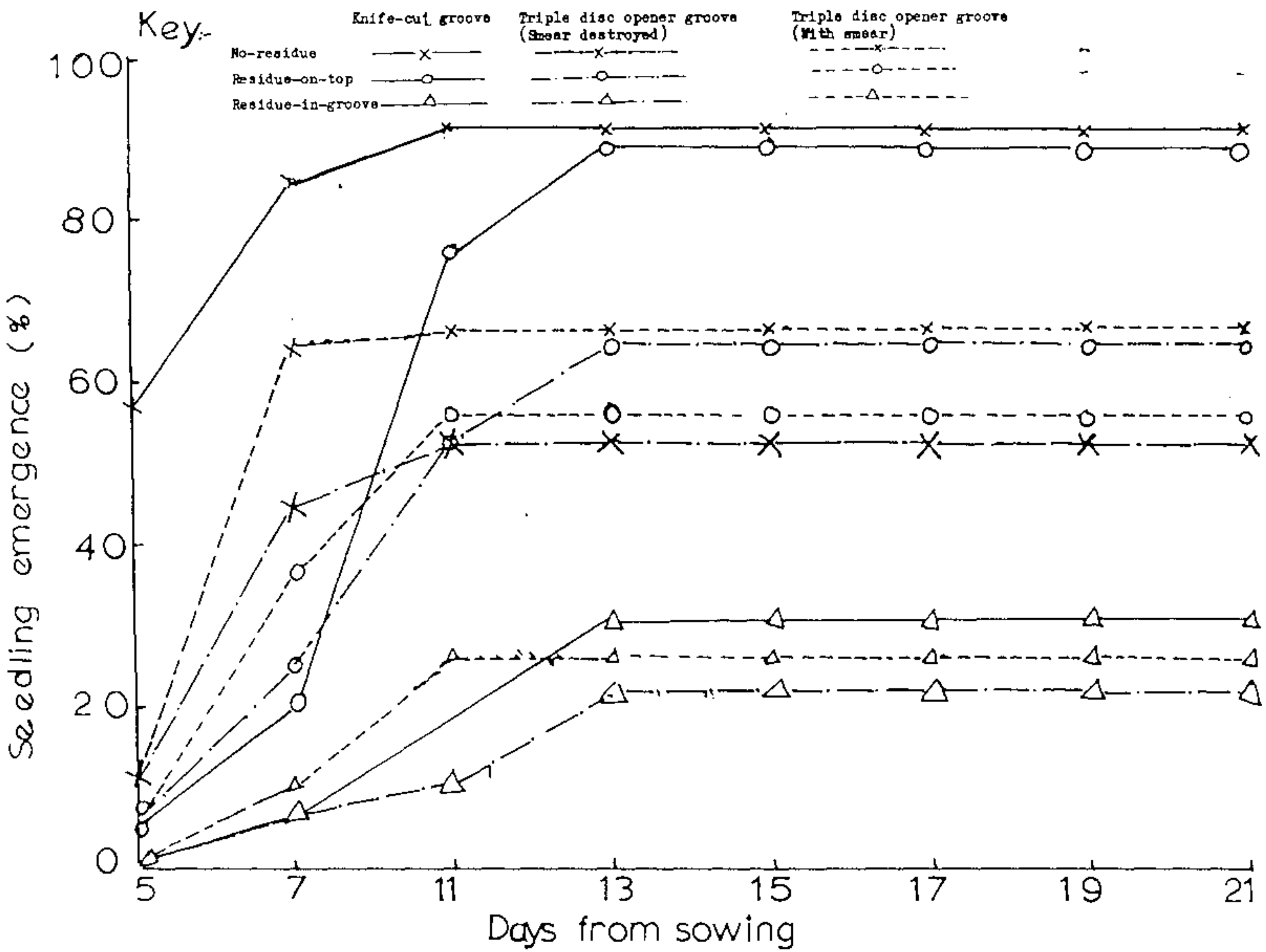


Figure 60: Effects of different methods of creating "V" shaped grooves, and position of crop residue , on seedling emergence rates of barley, under simulated rain conditions.

clear that residue in the groove was the strongest deterrent to seedling emergence.

Figure 60 shows the rates of seedling emergence as affected by the contrasting methods of creating "V"-shaped grooves under the three crop residue conditions. It appears that all "no-residue" conditions plateaued on day 11. Two other types of the grooves also plateaued on this day. These were triple disc with smear ("residue-on-top") and triple disc with smear ("residue-in-groove"). The latter treatment, however, attained a very low maximum emergence. All other treatments plateaued on day 13.

It appears from the curves that the treatments which showed the lowest maximum emergence rates all involved residue pushed into the grooves. The treatments with the highest maximum emergence counts also showed the most rapid rates of emergence during the first 5 days.

(b) Ungerminated/dead seeds:

Table 53 also lists the effects of "V"-shaped groove types and contrasting crop residue conditions, on ungerminated/dead seeds, and the interactions between these two parameters. The Table shows a highly significant ($P<0.01$) effect of groove types on ungerminated/dead seeds. The grooves cut with a knife showed the lowest numbers of ungerminated seeds (15.4%) compared with the grooves created by the triple disc opener with smear (25.6%) and the same with no-smear (26.7%), which were not significantly different.

The contrasting crop residue coditions had a significant ($P<0.01$) effect on the percentage of ungerminated/dead seeds. The "residue-in-groove" showed a significantly larger number of ungerminated/dead seeds (43.9%) than either the "residue-on-top" (11.6%) or "no-residue" (12.2%) conditions. It was considered likely that, as before, this might have been due to the reported phytotoxic effects of the decomposing crop residue in contact with the seed in wet soils (Ellis <u>et al</u>, 1975; Lynch, 1977,1978; Lynch <u>et al</u>, 1980).

There appeared to be strong interactions between groove types and contrasting surface residue conditions. Grooves with "residue-in-groove" consistently showed the highest number of ungerminated/dead seeds. This supports the possibility of phytotoxic effects from decomposing crop residue. By contrast, clearly the least seed damage occurred in the knife-cut grooves with either "no-residue" or "residue-on-top" of the groove, compared with all combinations of other treatments.

(c) "Germinated but unemerged" seedlings:

Table 53 also lists the effects of groove types and contrasting crop residue conditions, on "germinated but unemerged" seedlings, and the interactions between these parameters. It appears from the Table, that the knife-cut grooves showed significantly ($P<0.01$) less "germinated but unemerged" seedlings (12.9%) compared with the grooves created by the triple disc opener with (25.0%) or without (26.7%) smear.

The contrasting crop residue conditions had a highly significant ($P<0.01$) effect on "germinated but unemerged" seedlings. The "residue-in-groove" showed the highest numbers of "germinated but unemerged" seedlings (30.0%) compared with the "residue-on-top" (17.3%) and "no-residue" (17.2%) conditions.

There appeared to be reasonably strong interactions between treatments. Generally, these interactions favoured the same combinations of treatments as for ungerminated seeds. This suggests that the beneficial effects of the knife-cut groove with the "residue-on-top", or "no-residue", had affected seedling survival in a similar manner to seed germination.

(d) Dry matter weight of roots:

Table 54 shows the effects of the various "V"-shaped groove types and contrasting crop residue conditions on root weights per plant and the interactions between groove types and surface residue conditions. The knife-cut grooves showed significantly ($P<0.01$) higher root weights per plant (22.3 mg) than the grooves created by the triple disc opener with no-smear (17.4 mg) and with smear (17.5 mg), which were not significantly different.

The contrasting surface residue conditions had a highly significant

Table 54: Effects of "V" shaped groove types and crop residue conditions, on dry matter weights of roots and shoots of barley, under simulated rain conditions.

	"V" shaped groove types			Residue			Interactions				
	Knife cut	Opener created (SD#)	Opener created (S##)	NR*	RT**	RI***	Grooves/ Residue	Knife cut	Opener created (SD)	Opener created (S)	
Root Weight (mg)	22.3	17.4	17.5	20.8	23.5	12.8	NR	24.0	19.0	19.6	
	Aa	Bb	Bb	Bb	Aa	Cc	RT	30.0	20.6	20.0	SED=1.53
							RI	13.0	12.6	13.0	
Shoot weight (mg)	55.0	48.7	47.6	57.0	63.1	31.3	NR	62.6	53.6	54.6	
	Aa	Bb	Bb	Ab	Aa	Bc	RT	70.0	61.0	58.3	SED=3.92
							RI	32.3	31.6	30.0	

*NR = No surface residue present
**RT = Surface residue on top of the grooves
***RI= Surface residue pushed into the grooves
#SD = Smear destroyed
##S = Smear present
Unlike letters in a row denote significant differences (upper case, P<0.01; lower case, P<0.05).
SED=Standard error of all interactive differences.

(P<0.01) effect on dry matter weights of roots. The "residue-on-top" showed a significantly higher root weight (23.5 mg) compared with "no-residue" (20.8 mg), which itself was significantly higher than "residue-in-groove" (12.8 mg).

The interactions between groove types and contrasting surface residue conditions appeared to show a consistent trend of low yields with the residue in the groove.

(e) Dry matter weight of shoots:

Table 54 also shows the effects of groove types and contrasting crop residue conditions, on shoot weights per plant, and the interactions between these parameters. From the Table, it appears that there were highly significant (P<0.01) effects of groove types on shoot weights per plant. The knife-cut grooves showed a significantly higher shoot weight per plant (55.0 mg) compared with the grooves created by the triple disc, both with no-smear (48.7 mg) and with smear (47.6 mg). The latter two grooves were not significantly different.

The contrasting surface residue conditions had a highly significant (P<0.01) effect on shoot weight per plant. The "residue-on-top" of the groove showed a significantly higher shoot weight (63.1 mg) compared with "no-residue" (57.0 mg) and "residue-in-groove" (31.3 mg). The "no-residue" also displayed significantly (p<0.05) higher shoot weights than "residue-in-groove".

There appeared to be strong interactions between groove types and contrasting surface residue conditions. The strongest trend was for the lowest shoot weights to be consistently associated with "residue-in-groove". Perhaps the single highest weight was from the combination of knife-cut grooves and "residue- on-top".

(f) Oxygen diffusion rate (ODR)
around the groove profiles:

Table 55 shows the effects of the contrasting "V"-shaped groove types and groove/residue conditions, on ODR regimes around the groove profiles, and the interactions between these parameters. From the Table

Table 55: Effects of "V" shaped groove types and crop residue conditions, on oxygen diffusion rate (ODR), under simulated rain conditions.

Days from sowing	"V" shaped groove types: Knife cut	Opener created (SD#)	Opener created (S##)	Residue: NR*	RT**	RI***	Interactions: Grooves/ Residue	Knife cut	Opener created (SD)	Opener created (S)	
	ODR (gx10/cm/min) -8 2										
1	33.2	29.1	28.1	31.8	29.8	28.9	NR	35.2	31.0	29.2	
	Aa	Bb	Bc	Aa	Bb	Bc	RT	33.0	28.4	28.1	SED=0.84
							RI	31.5	28.1	27.1	
7	17.2	14.3	14.5	14.9	16.3	14.7	NR	17.0	14.1	13.7	
	Aa	Bb	Bb	Bb	Aa	Bb	RT	18.5	15.1	15.3	SED=0.44
							RI	16.2	13.7	14.4	
15	15.6	13.9	14.4	13.9	15.3	14.7	NR	14.5	13.3	15.5	
	Aa	Bb	Bb	Cc	Aa	Bb	RT	16.7	14.3	14.2	SED=0.52
							RI	13.8	15.1	14.4	
21	15.9	13.7	13.3	13.7	15.1	14.2	NR	14.4	13.4	13.2	
	Aa	Bb	Bb	Bb	Aa	Bb	RT	17.4	14.3	13.5	SED=0.42
							RI	16.0	13.5	13.1	

*NR = No surface residue present
**RT = Surface residue on top of the grooves
***RI= Surface residue pushed into the grooves
#SD = Smear destroyed
##S = Smear present
Unlike letters in a row denote significant differences (upper case, P<0.01; lower case, P<0.05).
SED=Standard error of all interactive differences.

Key:-

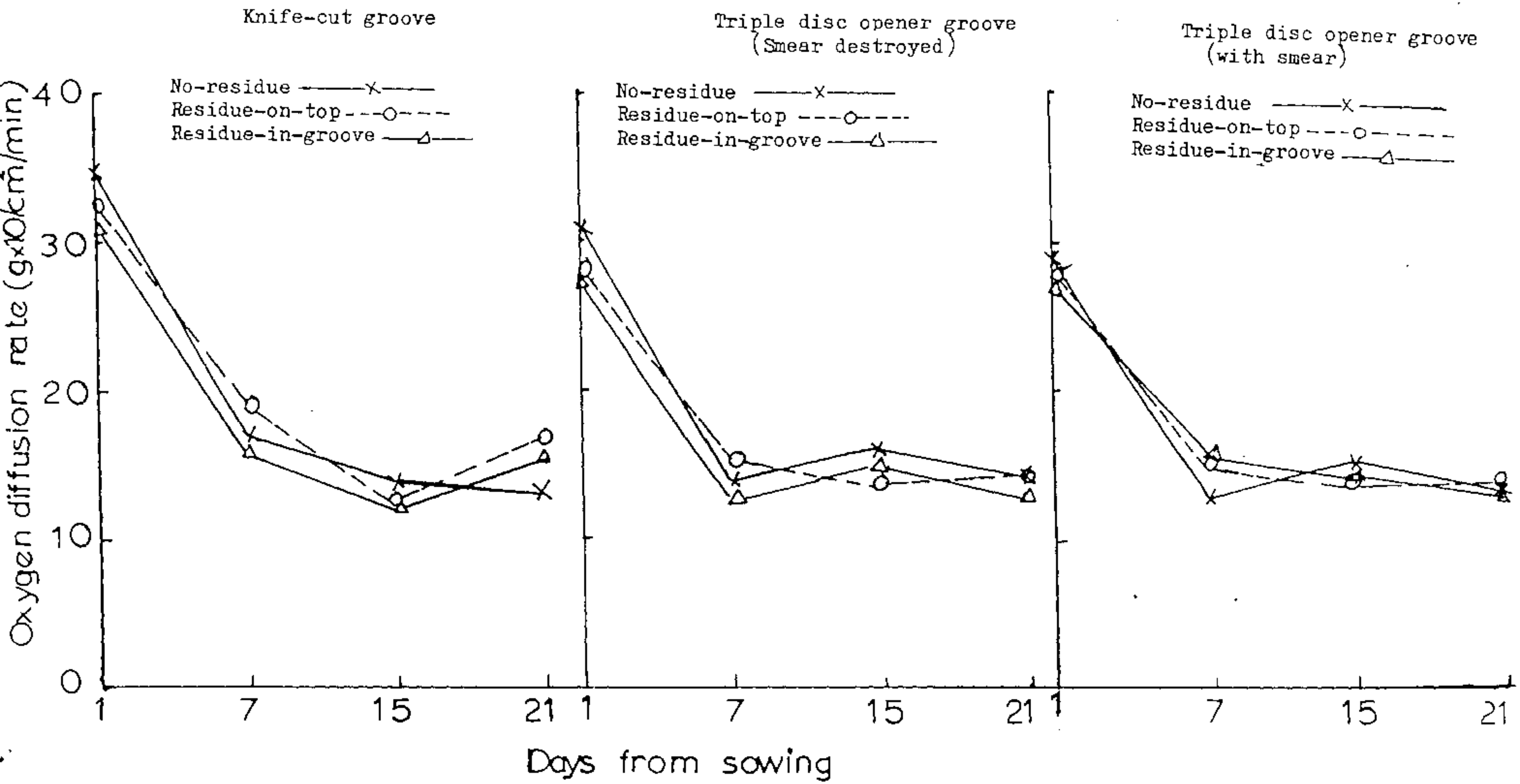


Figure 61: Effects of different methods of creating "V" shaped grooves, and position of crop residue, on oxygen diffusion rate (ODR) changes with time, around the groove profiles, under simulated rain conditions.

it appears that on days 1,7,15 and 21 the ODR regimes around the knife-cut grooves were significantly ($P<0.05$) higher than around the grooves created by the triple disc opener with no-smear, which except for day 1, were not significantly different from the same grooves with a smear.

The contrasting groove/residue conditions had a highly significant ($P<0.01$) effect on the mean ODR measurements around the groove profiles. While on day 1, the grooves with "no-residue" showed significantly the highest ODR, on all subsequent readings the grooves with "residue-on-top" had clearly the highest ODR regimes. The grooves with "no-residue" and "residue-in-groove" were not significantly different on days 7 and 21.

The interactions between "V"-shaped groove types and contrasting groove/residue conditions showed that in the main on almost all sampling days, the main treatment effects had been consistent across all subtreatments.

Figure 61 shows the ODR regime changes for each groove type with time under the contrasting crop residue conditions. It appears from all curves that between days 1 and 7, there was a rapid reduction in mean ODR values under all three contrasting residue conditions. However, the knife-cut grooves under "residue-on-top" and "residue-in-groove" tended to rise again between days 15 and 21. This might have been due to greater earthworm activity around the knife-cut groove (because of the absence of smearing and the presence of residue, compared with other treatments). The effects of soil smearing on earthworm activity have been discussed in Section 3.7.

By contrast, ODR values around the groove profiles where the triple disc opener had been used (without or with smear, and/or residue) continued to decline except for a small rise in ODR values between days 15 and 21 under "residue-on-top" conditions.

(g) Earthworm populations around
the groove profiles:

Table 56 shows the effects of the contrasting "V"-shaped groove types and groove/residue conditions, on earthworm populations around the

Table 56: Effects of "V" shaped groove types and crop residue conditions, on earthworm populations around the groove profiles, under simulated rain conditions.

"V" shaped groove types			Residue			Interactions				
Knife cut	Opener created (SD#)	Opener created (S##)	NR*	RT**	RI***	Grooves/ Residue	Knife cut	Opener created (SD)	Opener created (S)	
Populations per core###										
18.9	9.9	8.7	9.9	16.0	11.7	NR	13.0	8.7	8.0	
Aa	Bb	Bb	Bc	Aa	Bb	RT	25.0	13.0	10.0	SED=1.36
						RI	18.7	8.0	8.3	

*NR = No surface residue present
**RT = Surface residue on top of the grooves
***RI= Surface residue pushed into the grooves
#SD = Smear destroyed
##S = Smear present
Core volume = 1.13 litres.
Unlike letters in a row denote significant differences (upper case, P<0.01; lower case, P<0.05).
SED=Standard error of all interactive differences.

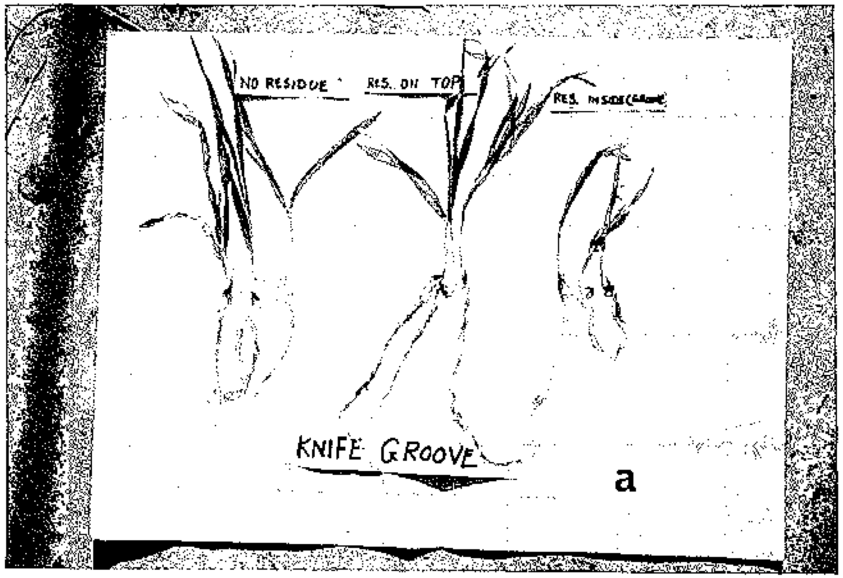
groove profiles, and the interactions between these parameters. It appears from the Table that the knife-cut grooves had a significantly larger number of earthworms around the groove profiles (18.9) than the grooves created by the triple disc opener with (8.7) or without (9.9) smearing, which were not significantly different.

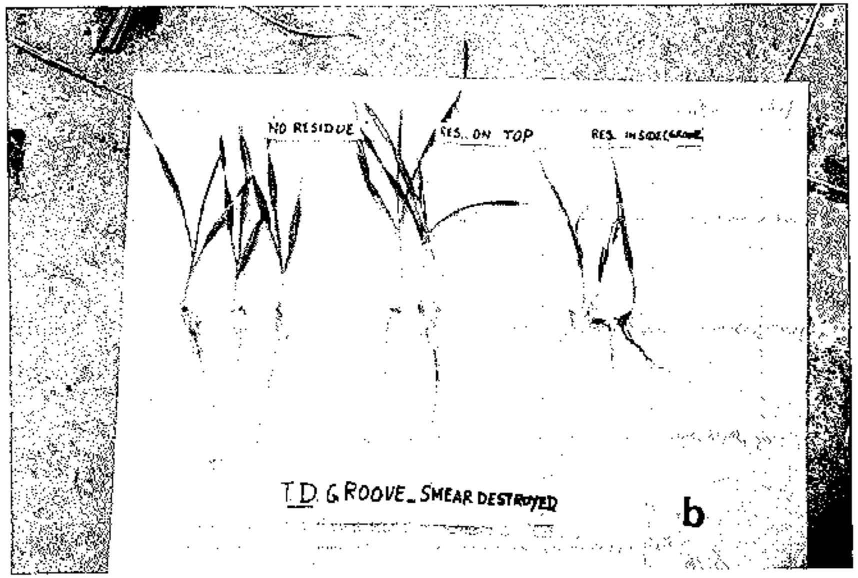
The contrasting surface residue conditions had a highly significant ($P<0.05$) effect on the numbers of earthworms around the groove profiles. The "residue-on-top" encouraged the most earthworms (16.0) followed by "residue-in-groove" (11.7), which was significantly higher than the "no-residue" (9.9) conditions. These data were dominated by the knife cut grooves, which because of the absence of smearing or compaction, favoured residue addition (even in the groove). It might also confirm the suggession put forward that the later rise in ODR values in the knife-cut grooves with "residue-on-top" was attributable to earthworm activity.

The interactions between groove types and contrasting surface residue conditions confirmed the superiority of "residue-on-top" compared to "no-residue" and "residue-in-groove" conditions. With both of the grooves made by the triple disc opener, the numbers of earthworms under "no-residue" or "residue-in-groove" were little different. The triple disc opener groove (smear destroyed) with "residue-on-top" recorded more numbers of earthworms compared with the triple disc opener groove with all other treatment combinations. With the knife-cut grooves, however, there were higher numbers of earthworms in "residue-in-groove" than "no-residue" conditions, even although some earthworm species were reported to be sensitive to an acid environment in the soil (Edward and Lofty, 1972; Piearce, 1972). The single largest number of earthworms was recorded in the knife-cut groove with "residue-on-top".

3.9.4 Discussion of Experiment 18:

It appears that in the grooves of the triple disc opener two factors were detrimental to seedling emergence and root/shoot weights of the emerged seedlings. These factors were smearing and perhaps compaction within the groove and the presence of crop residue pushed inside the groove. The decomposing crop residue inside the groove, regardless of





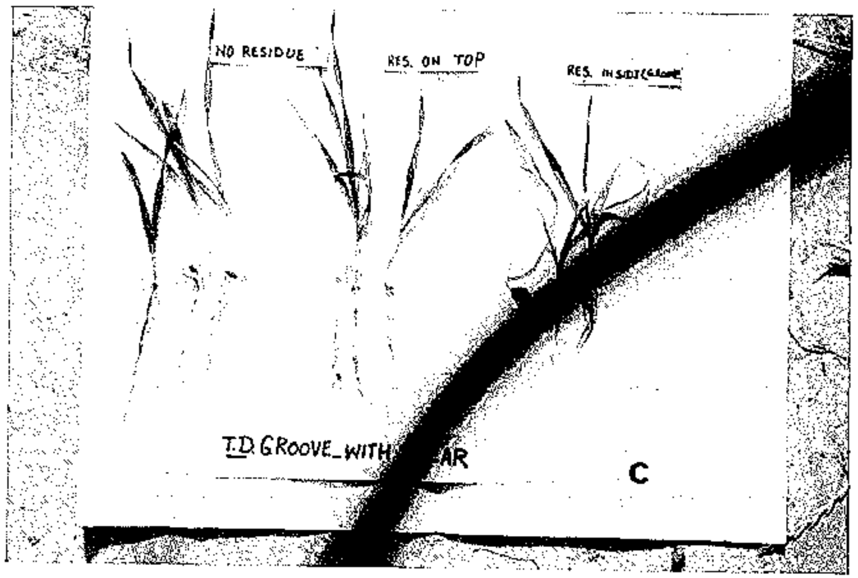


Figure 62 (a, b, c): Effects of different methods of creating "V" shaped groove, and position of crop residues on root/shoot development of barley.

(a). Grooves cut by hand with a knife.
(b). Grooves cut by triple disc opener- smear later destroyed
(c). Grooves cut by triple disc opener.

Note the adverse effects of "residue-in-contact" (inside); favourable effects of "residue-on-top" and no-residue" (particularly with knife-cut groove without smear).

groove smearing (and perhaps compaction), had an adverse effect on seed germination, seedling growth and root/shoot weights of the plants. Such decomposing crop residue had earlier been found to cause adverse effects on seed germination and seedling growth, regardless of the geometry and characteristics of the "V" or "U" shaped grooves (as discussed in Experiment 9, Section 3.3).

Figures 62 (a, b, c) illustrate the effects of "V" shaped groove types and the position of the crop residue. These Figures also show that root/shoot development was restricted in the grooves when residue was pushed inside the grooves to be in contact with the seed. The "residue-on-top" had markedly improved seedling performance compared with "no-residue".

Earlier experiments had also indicated the adverse effects of soil smearing and/or compaction on earthworm activity (Sections 3.2, 3.6 and 3.7). In particular, the triple disc opener groove, with its often smeared and/or compacted walls, had shown lower numbers of earthworms around the groove profiles compared to the grooves of other opener types. In the present experiment, it seems clear that these two environmental factors, which were somewhat hostile to earthworms (soil smearing and perhaps compaction, together with acidity in the grooves) existed at the same time around the groove profiles created by the triple disc opener. Perhaps this also led to the lower ODR regimes which were observed around the groove profiles of this opener, operating in residue in a wet soil. The "V"-shaped groove cut by a hand-drawn knife showed higher ODR regimes than where the triple disc opener had been used, both with and without an associated smear. It is probable that such a smear represented the peripheral layer of more extensive compaction around this groove (as identified by Mai, 1978). Other workers had also reported adverse effects of soil compaction on ODR values (Bertrand and Kohnke, 1957; Taylor, 1949; Raney, 1949). However, the effects of soil aggregates and soil moisture could also be important, according to Taylor, (loc cit).

It is possible that low seed germination and seedling growth recorded in the grooves of the triple disc opener might have been due to the adverse effects of lower ODR values in the vicinity of the groove profiles. On the other hand the low ODR values may themselves have been a result of low earthworm activity and/or smearing and compaction caused by the opener.

4. SUMMARY AND DISCUSSION

An understanding of the interrelationship between soil physical factors, seed germination and seedling emergence was thought to be fundamental to the functional design of seed drill openers. This project was initiated against a background of limited published data concerning the effects of different direct drilling furrow openers on the micro-environments at or near the seed-soil interface, and any interactions between seed germination and seedling emergence in the presence or absence of surface residue and earthworms, under wet warm soil conditions.

The objective of this study was to identify and characterise the salient soil physical parameters which might have been altered by the actions of different designs of direct drilling openers; and in turn to note the effects that these had on the germination and emergence of barley seedlings. To the extent that these factors could be influenced by mechanical design, such information was felt to be a valuable pre-requisite for improvement to planter designs.

The research work was conducted under four basic experimental conditions. These were:

(a) Field experiments comparing opener performance, seed/seedling micro-environment, earthworm activity and infiltration rate under variable prevailing climatic conditions.

(b) Laboratory (glasshouse) studies of seedling emergence, earthworm activity and seed/soil micro-environments, conducted at an ambient temperature of 20-25 ^{o}C and simulated rainfall of 20 mm per day for 21 days.

(c) Laboratory (glasshouse) studies of seedling emergence, earthworm activity and seed/soil micro-environments, conducted at an ambient temperature of 20-25 ^{o}C and temporary high water table conditions with added soil water equivalent to 20 mm a day for 21 days.

(d) Laboratory (glasshouse) studies of seedling emergence, earthworm activity and seed/soil micro-environments conducted at an ambient temperature of 15-20 ^{o}C and simulated rainfall of 20 mm a day for 21 days.

In all experiments the seed was drilled under "available" soil moisture conditions, which (except for the unirrigated portion of the field experiment) was followed by sufficient regular daily precipitation to ensure that very wet soil conditions prevailed.

The results showed clearly that there were three important inter-related variables. These were: opener types, which influenced the geometry and other characteristics of direct drilled grooves; the presence of earthworms; and crop residue. All of these factors were important in relation to seedling emergence and the seed/soil environments around the grooves under wet soil conditions.

With all the parameters monitored there were few if any differences recorded when the added soil water was changed from simulated rain (experimental condition b above) to temporary high water table (experimental condition c above). Thus, effectively, comparisons are described below, in terms of three basic experimental conditions which varied mainly in their ambient temperature regimes (although the field experiment also experienced largely unpredictable soil water conditions).

4.1 OPENERS

Each opener type used in the field and laboratory experiments created a groove of identifiable characteristics and shape.

The winged opener created an inverted "T" shaped groove (in cross section) with subsurface shattering of soil and repositioned the surface soil over the groove (from whence it came) which then became closed to the atmosphere. In so doing this type of groove also returned the crop residue to the area above the groove.

The hoe opener created a "U" shaped groove, which was not compacted and during its formation, residue was swept to either side of the groove and the groove remained open to the atmosphere. No attempt was made to cover such grooves under the prevailing wet conditions.

The triple disc opener created a "V" shaped groove which was open to the atmosphere and was known to be compacted or smeared at the base and sides (Baker and Mai, 1982). This type of opener pushed a portion of the residue into the groove in the seeding zone.

The power-till opener created a wide groove (100 mm) using a powered "L" blade configuration rotating in the forward direction of travel. In so doing, it incorporated crop residue with pulverised soil but created no obvious smearing, and clearly provided a strip of tilled soil for the seed. This type of groove might have created some degree of soil compaction at the base of the groove, as is typical of large "L" blade configurations, but no measurements were made of this.

The simulated punch planter opener (using a cylindrical corer) created discrete and regular narrow "U" shaped holes which were open to the atmosphere. These holes appeared to be created without compaction or smearing on their sides or bases and no crop residue was pushed inside the holes. However, this might not be typical of other field punch planters such as that described by R. Lal (pers. comm, 1982), which used more of a wedging action.

A surface-broadcasting technique was also used later in the study. In this treatment, the seed was spread uniformly on the undisturbed/untilled soil surface which was either covered with crop residue or was left bare.

In both the field and laboratory experiments there were significantly different effects of opener types on seedling emergence and seed/soil environments around the groove profiles, but these were confined almost entirely to when earthworms were present. The performances of the grooves of each opener types are summarised below in descending order.

Tables 57a (in the presence of earthworms) and 57b (in the absence

Table 57a: Summary of interactive responses of direct drilled barley seeds to opener types, crop residue and earthworms in a saturated soil.
(Percentage seedling emergence)

PRESENCE OF EARTHWORMS:

Experiments	Residue	Opener types: Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broad-casting
Field Expt. (Irrigation) Sec. 3.1	No-residue	47.0	38.3	41.7	NOT TESTED		
	Residue	75.0	30.0	67.7			
					SED1=4.26; SED2=3.26		
Tillage bin (Glasshouse-simulated rain) Sec. 3.2	No-residue	43.8	26.2	32.9	NOT TESTED		
	Residue	73.3	25.2	63.8			
					SED1=3.15; SED2=1.07		
Tillage bin (Glasshouse-Temporary high water table) Sec. 3.3	No-residue	35.7	57.1	31.9	NOT TESTED		
	Residue	73.8	27.1	60.5			
					SED1=5.12; SED2=5.52		
Pot Expt. (Glasshouse-simulated rain) Sec. 3.4	No-residue	53.3	63.3	66.7	NOT TESTED		
	Residue	86.7	56.7	88.3			
					SED1=5.77; SED2=6.87		
Tillage bin (Glasshouse-simulated rain) Sec. 3.6	No-residue	48.0	24.7	40.0	62.0	14.7	86.7
	Residue	75.3	17.3	64.7	62.7	17.3	84.0
					SED1=6.15; SED2=7.16		

SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

Table 57b: Summary of interactive responses of direct drilled barley seeds to opener types, crop residue and earthworms in a saturated soil. (Percentage seedling emergence)

ABSENCE OF EARTHWORMS:

Experiments	Residue	Opener types					
		Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broad-casting
Pot Expt. (Glasshouse-simulated rain) Sec. 3.4	No-residue	63.3	53.3	60.0	NOT TESTED		
	Residue	50.0	40.0	56.7			
					SED1=15.15; SED2=9.43		
Tillage bin (Glasshouse-simulated rain) Sec. 3.6	No-residue	22.0	18.7	22.7	41.3	16.0	88.7
	Residue	20.0	15.3	24.0	43.3	14.0	89.3
					SED1=1.53; SED2=1.65		

SED1=Standard error of difference within opener types.
SED2=Standard error of all other interactive differences.

Table 58: Summary of interactive responses of earthworms to direct drilling opener types and crop residue in a saturated soil. (Earthworm populations around the groove profiles)*

Experiments	Residue	Opener tyeps					
		Winged	Triple disc	Hoe	Power-till	Punch planter	Surface broad-casting
Tillage bin (Glasshouse-simulated rain) Sec. 3.2	No-residue	13.3	6.7	11.3	NOT TESTED		
	Residue	27.3	8.0	26.7			
					SED1=2.49; SED2=1.79		
Tillage bin (Glasshouse-Temporary high water table) Sec. 3.3	No-residue	15.0	8.7	16.3	NOT TESTED		
	Residue	29.1	10.7	30.0			
					SED1=2.18; SED2=1.97		
Pot Expt. (Glasshouse-simulated rain) Sec. 3.4	No-residue	19.3	16.7	14.7	NOT TESTED		
	Residue	25.3	25.7	28.3			
					SED1=6.10; SED2=5.27		
Tillage bin (Glasshouse-simulated rain) Sec. 3.6	No-residue	12.7	8.0	12.7	14.3	10.0	13.7
	Residue	24.7	9.3	22.0	23.0	18.3	22.3
					SED1=2.06; SED2=2.17		

SED1=Standard error of difference within opener types.
SED2=standard error of all other interactive differences.
*Note: The pot experiment did not have the same unit soil mass from which earthworm populations were counted, as the other 3 experiments listed.

of earthworms) show interactive responses of direct drilled barley seeds; and Table 58 shows the interactive responses of earthworms, to direct drilling seed sowing techniques and contrasting crop residue conditions in a saturated soil.

(a) Surface broadcasting:

Surface broadcasting was included to provide an "unlimited" atmospheric oxygen treatment in these situations. It is a treatment, however, not known to be used in practice with "direct drilled" cereals in untilled soils. In the two experiments in which six direct drilling seed sowing techniques were compared (in the presence or absence of earthworms; both at 15-20 ^{o}C), the technique which involved surface broadcasting onto untilled soil gave the highest overall seedling emergence of all direct drilling seed sowing techniques. However, in the presence of earthworms and crop residue the winged opener had an equivalent performance to surface broadcasting. In the presence of earthworms, but in the absence of crop residue, surface broadcasting gave clearly the highest maximum emergence of all direct drilling seed sowing techniques. Similarly, in the absence of earthworms, and under both residue and no-residue conditions, the surface broadcasting technique gave the highest maximum emergence of all direct drilling seed sowing techniques. In fact, in the absence of earthworms and residue, surface broadcasting gave more than twice the seedling emergence of the best of the "true" openers (power-till). This was probably due to "unlimited" atmospheric oxygen, the warm temperature and consistent frequent rain (which in these experiments was 20 mm a day for 21 days). Under the prevailing experimental conditions, the surface broadcasting technique must be regarded as having been successful, regardless of the presence or absence of earthworms or surface residue. This treatment however, would be of limited practical importance in the field (for sowing cereals in untilled soil) because of the limited potential for 'seed-soil contact' and thus possible reliance on duplication of the experimental conditions for germination. No attempt was made to examine the potential of this treatment in other environments.

The surface broadcasting technique in the presence of earthworms and residue, showed lower final oxygen diffusion rates (ODR) than the grooves of all openers except the triple disc. This might indicate that the unlimited availability of oxygen above the soil in the surface broadcasting treatment more than compensated for any low soil ODR, as the seeds were largely isolated from the true soil environment. On the other hand, once the radicle had penetrated into such a soil environment, seedling performance might have been expected to respond in a similar manner to drilled seeds. Indeed root/shoot weights reflected this effect as the surface broadcasting treatment ranked only second or third (to the power-till treatment) in these respects.

(b) Winged opener:

In three of the four experiments in which only the three main opener types were compared (winged, triple disc, hoe), seedling emergence performance of the winged opener grooves in the presence of earthworms and residue was the highest of the three opener types. In the remaining one experiment it was equal to the hoe opener as the highest. In a further experiment in which the range of direct drilling seed sowing techniques was extended to six, the winged, hoe and power-till openers in the presence of earthworms and residue performed equally well. The winged opener, however, was also equivalent to the highest ranked surface broadcasting in this specific situation (as earlier described). In the presence of earthworms and surface residue, the grooves of the winged opener showed 2-4 fold increases over those of the triple disc and punch planter openers; but this difference was all but eliminated in the absence of earthworms. In the absence of earthworms the grooves of the winged opener were inferior to those of the power-till opener, in terms of seedling emergence.

In a total of five experiments, the winged opener showed no significant differences in earthworm populations, ODR regimes and soil bulk densities around the groove profiles compared with the hoe opener grooves, but together these two openers recorded the most favourable measurements of these factors. In these five experiments the winged opener averaged 2 fold greater numbers of earthworms, 24% higher ODR values and 9% lower soil bulk densities than the triple disc opener grooves.

In the presence of earthworms, and with two infiltrometer depths (100 and 140 mm) the winged opener showed a higher cumulative infiltration than any other opener type, and the undisturbed soil surface, both in residue and no-residue conditions. For example, the winged opener in the presence of earthworms, under no-residue conditions and with an infiltrometer depth of 100 mm, showed an approximately twice the cumulative infiltration compared to the average of all other direct drilling seed sowing techniques. Similarly, under residue conditions this opener showed 50% higher cumulative infiltration compared to the average of all other treatments. Furthermore, in the absence of earthworms and surface residue the groove of the winged opener showed significantly higher cumulative infiltration than any other seed sowing technique, but only with a 100 mm infiltrometer depth. With a 140 mm infiltrometer depth there were no significant differences in cumulative infiltration amongst seed sowing treatments in the absence of earthworms and residue.

The performance of the grooves of the winged opener was thought to have been due to the inverted "T" shaped grooves, which shattered the soil beneath the surface and retained the residue over the top of the grooves (and thereby avoided residue contact with the seeds). It is thought that this might have attracted a greater number of earthworms to the groove profile which improved the seed-soil environment, thereby helping to promote seed germination and seedling emergence.

(c) Hoe opener:

Although in the presence of earthworms and residue the seedling emergence performance of the hoe opener grooves was slightly inferior to that of the winged opener in some experiments, it also showed 2-3 fold increases in seedling performance compared with the grooves of the triple disc opener in the five experiments in which these three openers were compared. Again, however, these differences were all but eliminated in the absence of earthworms or residue. In the one experiment in which six direct drilling seed sowing techniques were compared the grooves of the hoe opener performed similarly to those of the power-till and winged openers. The former two were also lower than the surface broadcasting technique.

In all five experiments the mean oxygen diffusion rate (ODR), earthworm populations and soil bulk densities around the groove profiles of the hoe opener were identical to those of the winged opener, but as described above, this was not necessarily matched by seedling performance. In all five experiments, the hoe opener grooves showed significantly greater numbers of earthworms, higher ODR regimes and lower soil bulk densities than the triple disc opener. It appears that with the hoe opener grooves, even residue swept to either side of the grooves remained close enough to have contributed to earthworm populations and activity around the groove profiles.

(d) Power-till opener:

In the one experiment in which six direct drilling seed sowing techniques were compared (condition d above at 15-20 ^{o}C), the average seed/seedling performance of the power-till opener grooves in the presence of earthworms and residue was identical to that of the performance of the grooves of the winged and hoe openers (as earlier described). In the absence of earthworms and residue the power-till opener promoted the highest seedling emergence of all "true" openers, although it was less than half the values obtained following surface broadcasting. Clearly the power-till opener relied on physical disturbance, rather than the attraction of earthworms to create a desirable seed micro-environment, because in the absence of earthworms its grooves showed significantly higher seedling emergence than all other true opener designs (winged, triple disc, hoe and punch planter). Nevertheless, the seedling performance of the power-till was 20% less than that which it sustained in the presence of earthworms, although this was not affected by the presence or absence of crop residue. Such an effect might have been due to the wide shattering action of this opener and the fact that any surface residue present was incorporated by its action, thereby aiding aeration.

In the presence of earthworms soil bulk densities around the groove profiles of the power-till opener were similar to the grooves of the punch planter opener and surface broadcasting technique. However, the ODR values around the groove profiles of the power-till opener, in the presence and/or absence of earthworms were higher than any other direct drilling seed sowing technique during the experimental period. The power-till opener had similar earthworm numbers to the winged and hoe openers and surface broadcasting, but showed greater earthworm numbers than the triple disc and punch planter openers. The relatively high earthworm numbers around the groove profiles of the power-till opener, compared with the triple disc and punch planter openers, might have been due to the wide shattered grooves of the power-till (despite some probable killing of earthworms by its action). By contrast, there was compaction and smearing with the triple disc opener, and puddling of water in the discontinuous holes of the punch planter opener, which might have discouraged earthworms, but not killed them.

(e) Triple disc opener:

In all the experiments in which the triple disc opener was compared with the winged and hoe openers in the presence of earthworms and residue, its groove performed poorly in terms of seedling performance, ODR regimes and earthworm populations around the groove profiles. It also compared poorly with the power-till and surface broadcasting treatments in the one experiment in which they were also involved. However, in this latter experiment the grooves of the triple disc opener showed no significant difference in seedling emergence compared with the grooves of the punch planter opener. The triple disc opener created smearing and compaction which resulted in higher soil bulk density readings around the groove profiles compared with all other direct drilling seed sowing techniques (including the punch planter opener).

The triple disc opener was observed to push residue inside the grooves, where they remained in contact with some of the seeds. The resulting phytotoxicity of decomposing residue might have been responsible for the adverse effects on seed germination and seedling emergence, especially when operating in residue conditions. Such phytotoxic effects, therefore, appear to be relevant to wet soil conditions, ranging from the cold autumn temperatures of the United Kingdom to the warm (15-25 ^{o}C) conditions used in these experiments.

It had earlier been reported by Mai (1978), and Baker and Mai (1982) that soil compaction and/or smearing were detrimental to seedling emergence. Cutting a "V" shaped groove with a knife (in such a way that smearing and compaction was minimised) significantly improved seedling emergence, root/shoot weights, ODR regimes and earthworm populations around the groove profile, compared with when such a groove was created by a triple disc opener with a plain front disc. Similarly, when residue was artificially placed over the top of "V" or "U" shaped grooves, improved seedling emergence counts and seed/soil micro-environments resulted, compared with where the residue was artificially pushed into the grooves, which was detrimental to seedling emergence. This occurred whether the "V" shaped groove was knife-cut or created by a triple disc opener.

(f) Punch planter opener:

In the one experiment in which six direct drilling seed sowing techniques were compared, in the presence of earthworms and residue, the seedling performance of the "grooves" of the punch planter opener was inferior to all other opener types and the surface broadcasting technique, except the triple disc opener. Similarly, this opener showed lower ODR values and earthworm populations around its "groove" profiles compared to all other direct drilling seed sowing techniques, except the triple disc opener grooves which showed lower ODR values and almost 2 fold lower numbers of earthworms than the punch planter opener. The punch planter opener in the presence of residue and earthworms also showed a lower soil bulk density than the triple disc opener, but was higher in this respect than the winged and hoe openers. The improved performance of the punch planter opener compared with the triple disc opener (in terms of ODR values, earthworm populations and soil bulk densities) might have been due to the nature of its "grooves" which were a series of uncompacted and/or unsmeared discontinuous holes, compared to the continuous wedged nature of the triple disc opener grooves.

4.2 CROP RESIDUE

Both field and laboratory experiments indicated that the presence or absence of crop residue on the soil surface influenced seedling emergence and the seed-soil micro-environment in the presence of earthworms. In this respect, crop residue conditions showed 28% higher seedling emergence, 40% increased root weights, 27% higher ODR regimes, 70% greater earthworm populations and 25% greater area index of their casts, together with 8% lower soil bulk densities around the groove profiles, than no-residue conditions.

The experiments also showed that seed/residue contact was an important aspect of the geometry of the grooves in affecting seed germination and seedling emergence. For example, the performances of both the triple disc opener grooves ("V" shaped) and hoe opener grooves ("U" shaped), in terms of seedling emergence and root weights, were significantly improved when residue was present but was prevented from contacting the seed (by artificially removing them from inside the triple disc grooves and placing them, instead, over the grooves; the hoe opener did not push the residue into the grooves in the first place) compared to when the residue was artificially pushed into the grooves. For example, the residue placed over the groove showed 70 % higher seedling emergence and 54% greater root weights than when residue was pushed into the groove. The major problem which arose when residue was pushed into the grooves in contact with the seed, was ungerminated or dead seeds under the prevailing wet soil conditions.

The beneficial effects of the presence of residue were most pronounced with the winged opener, when earthworms were present. This opener returned the residue to approximately its original position on the soil, thereby covering the groove. It was thought that the beneficial response of earthworms to the position of the surface residue was the main reason this opener benefitted in this way, as the response in the absence of earthworms was minimal. The hoe opener was the next most beneficially influenced by the presence of residue. As this opener swept the residue aside, the reduced benefit compared with the winged opener is perhaps understandable. This opener too showed no response to residue in the absence of earthworms. All other direct drilling seed sowing techniques experienced either negligible response to residue (power-till, punch planter, surface broadcasting) or were disadvantaged by them (triple disc opener). The latter treatment also showed little response to the presence or absence of earthworms under residue conditions.

4.3 EARTHWORMS

A characteristic aspect of these experiments was that opener types and crop residue lost most of their influence on the seeds and seedlings in the absence of earthworms. In this sense earthworms could be considered to have been an important factor in affecting (either directly or indirectly) seed germination and seed-soil environments under wet soil conditions. For example, there were practically no significant effects of opener types or crop residue on percentage seedling emergence, root/shoot weights, oxygen diffusion rate regimes (ODR), soil bulk densities and soil moisture contents around the groove profiles in the absence of earthworms. These effects were difficult to quantify absolutely, as the presence or absence of earthworms constituted separate pairs of simultaneous (but otherwise identical) experiments.

Two particular experiments showed these effects, although in one of these experiments (which extended the number and range of direct drilling seed sowing techniques from 3 to 6) significant beneficial effects on all of the above parameters were shown by a power-till opener which tilled 2/3 of the soil area, together with a surface broadcasting treatment, in the absence of earthworms. Nevertheless, the differences that were attributable to direct drilling seed sowing techniques in the absence of earthworms, were minor by comparison with those which occurred in the presence of earthworms. Furthermore, the absolute performance of the "best" opener/residue treatments (excluding surface broadcasting) in the presence of earthworms was far greater than the "best" opener/residue treatments in the absence of earthworms. The mean of all direct drilling seed sowing techniques and residue conditions showed that the experiments with earthworms had 136% higher oxygen diffusion rates (ODR), and 34% greater seedling emergence counts than those without earthworms.

Three earthworm species (Allolobophora Longa, Allolobophora caliginosa and Lumbricus rubellus) were found to be most active in the top 100 mm of soil. This is thought to have been partially responsible for the higher infiltration rates shown with a shallow infiltrometer depth of 100 mm compared with 140 mm. For example, the average cumulative infiltration into drilled grooves using an infiltrometer depth of 100 mm was 60% (in residue) and 24% (in no-residue) greater than where an infiltrometer depth of 140 mm was used under these conditions in the presence of earthworms. In the absence of earthworms and surface residue the differences in average cumulative infiltration between the two depths was very small (10 mm). The cumulative effect of earthworms and residue on infiltration across all direct drilling seed sowing techniques (at an infiltrometer depth of 100 mm) was to increase total infiltration by 9 times compared to that recorded in the absence of both earthworms and residue. The presence of earthworms alone accounted for a 7 fold increase in infiltration. Thus it might be concluded that the ability of an opener to influence the presence of earthworms and crop residue is an important design determinant in affecting infiltration rates around the groove profiles.

This restricted zone of influence on infiltration may be explained by the apparent limited extent of effectiveness of each opener, and its associated earthworm activity and the changes which they brought to the seed/soil micro-environments (ODR, soil bulk density, soil moisture content) around the groove profiles. This zone appeared to be limited to 60 mm to either side of the grooves and a similar distance down from the groove bases.

Direct drilling seed sowing techniques had significant effects on earthworm populations only within this 60 mm square zone of soil centering on the base of the groove profile, under both residue and no-residue conditions. This observation, however, depended to some extent on the position of the crop residue (if any) and physical characteristics of the groove (particularly the extent of soil compaction around the groove profile).

Numbers of earthworms were not significantly different amongst those openers which avoided compaction around the grooves (winged, hoe and power-till). The "V" shaped triple disc opener grooves (which were compacted) showed 2 fold lower numbers of earthworms and 80% lower activity of earthworms than the mean of all other direct drilling seed sowing techniques. This opener also resulted in the lowest ODR and seedling emergence counts in both residue and no-residue conditions. This might have been a result of soil compaction or smearing by the opener. The punch planter opener had the second lowest numbers of earthworms even although it appeared to avoid compaction. Perhaps this reflected the puddling of water in its discontinuous holes. Disturbance from the power-till opener was maximized, but this effect may have been partially offset by the physical damage done to a number of earthworms.

Later experiments showed that under continuously wet soil conditions, a high degree of smear, together with high levels of soil bulk density, discouraged earthworm populations and activity. A similar negative effect on ODR at 40 mm depth was observed in these smeared and compacted soils. Absence of a smear, and a soil bulk density level of 1.0 g/cm^3, showed the highest earthworm activity and ODR of the conditions tested.

Under continuously drying soil conditions earthworm activity appeared to stop after 7 days, but up to that time the avoidance of a smear and maintenance of soil bulk density at 1.0 g/cm^3 encouraged more earthworm activity than where any form of smear existed or the bulk density level was higher than 1.0 g/cm^3.

Observations of the movements and activity of earthworms in partly smeared cylindrical holes showed that all earthworms were attracted towards surfaces without smears, rejecting those surfaces which were smeared. Together with other experiments involving earthworms, this seemed to suggest a sensitivity to smearing and/or compaction which occurred regardless of whether the earthworms were approaching or exiting from a soil surface. Such a sensitivity may explain the lower numbers of earthworms and reduced activity around the groove profile of the triple disc opener, which compacted and/or smeared the sides and base of the grooves.

It is possible that an acid environment (due to decomposing residue in the groove) may also have been hostile to earthworm populations and their activity. For example, the hoe opener groove with residue artificially pushed into the groove showed lower numbers of earthworms than when the residue was over the groove. On the other hand, the triple disc opener groove with residue pushed into the groove showed almost equal numbers of earthworms compared to when the residue was placed over the top of the groove. Overall, in this experiment the residue on top of the grooves showed 26% higher numbers of earthworms, compared to when residue was pushed into the groove.

4.4 CONCLUSIONS

The results of all field and glasshouse (laboratory) experiments showed a high level of consistency. From the results of these experiments the following conclusions could be drawn.

1. The geometry and characteristics of direct drilled grooves, together with the presence or absence of crop residue and the presence or absence of earthworms could all be expected to influence seed/soil micro-environments in wet soils.

2. In the presence of earthworms, strong beneficial effects from the presence of surface residue can be expected.

3. Such a benefit from surface residue will be negated if the residue is pushed into the groove in contact with the seed.

4. Under wet soil conditions containing earthworms and residue a shattered groove with crop residue over the top of the groove, such as that created by the winged opener (inverted "T" shaped groove), or in the vicinity of the groove (such as the "U" shaped groove of the hoe opener) will be beneficial in promoting seed germination, seedling emergence and a favourable seed/soil environment.

5. The success of the winged, hoe and power-till openers might be due to an improvement in ODR regimes and encouragement of more earthworms than the grooves of the triple disc opener, under wet soil conditions in residue.

6. In the absence of earthworms and regardless of surface residue, a power-till opener which tills a strip at least 100 mm wide, should result in a higher ODR and seedling emergence count than other opener

types.

7. Surface broadcasting of seed onto untilled seedbeds, despite its high level of emergence in these experiments, is not recommended as continuous or regular (daily) precipitation might be needed in the field over an extended period of time.

8. A direct drilled groove with compacted or smeared sides and/or base (such as that created by a triple disc opener) will be detrimental to seedling emergence and the seed/soil micro-environment around the groove profiles.

9. Physical disturbance, *per se*, is likely to be beneficial to earthworm activity in the groove, so long as it is not accompanied by compaction, smearing, puddling of water, pushing of residue into the groove or killing of large numbers of earthworms by the physical action of the opener.

10. Decomposition of crop residue under wet warm soil conditions, where it is in contact with the seed in the groove, and regardless of the geometry of the groove, will adversely affect seed and seedling performance (especially the former) in ambient temperature conditions ranging from 15-25 ^{o}C.

11. The narrow "U" shaped groove of a punch planter under wet soil conditions will perform poorly, even under crop residue, if the grooves remain filled with water for substantial periods.

4.5 RECOMMENDED FURTHER RESEARCH WORK

It is suggested that further research work should be conducted in the following areas.

(a) Further improvements of equipment and techniques for measurements of seed/soil micro-environments around the groove profile under wet warm conditions.

(b) Residue from different crops should be examined to evaluate their effects on seedling performance.

(c) Other sown crop species might be compared with barley used in this project in the wet warm test conditions.

(d) It was not clear whether soil compaction and low oxygen diffusion rates (ODR) simultaneously affected earthworms or whether earthworms were discouraged by soil compaction alone. Studies might seek to examine the individual roles of these parameters.

(e) The effects on earthworm activity of an acid environment from decomposing crop residue might be studied.

(f) Mathematical models might be established to further define oxygen diffusion rate (ODR) regimes around direct drilled groove profiles.

(g) The wet warm conditions might be varied to examine the effects of different groove depths and rain intensities.

(h) Further field experiments might be conducted to improve the reliability of extrapolating the laboratory findings in this project.

(i) Simple instrumentation should be devised to test the suitability of direct drilled grooves for given on-farm conditions involving wet soils after drilling. Oxygen diffusion rate would seem to be the most suitable parameter to monitor in the field.

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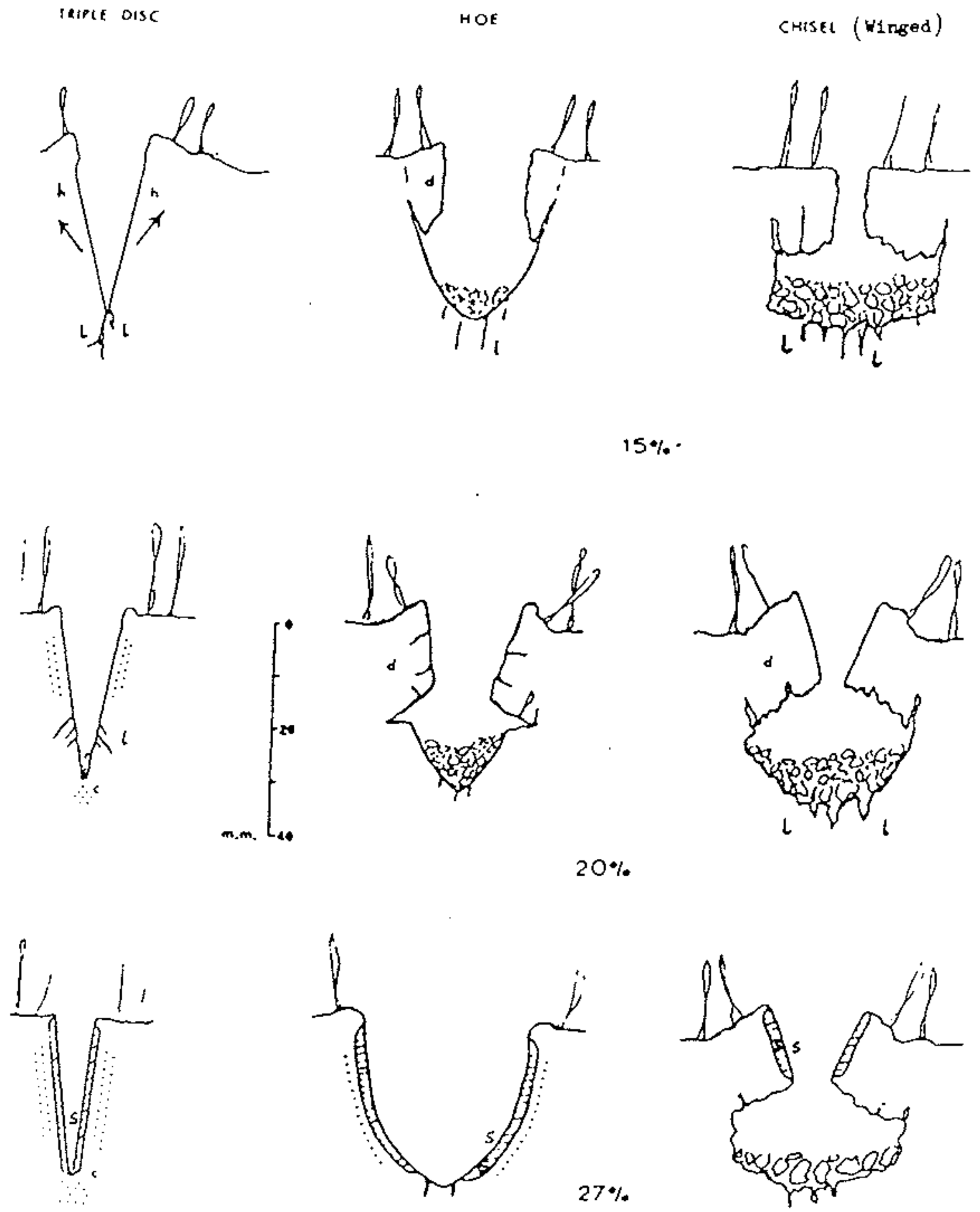
7. APPENDICES



Key:

h = Heaving of soil
d = Sod displacement during coulter passage
l = Loosening and cracking of soil
c = Zone of compaction
s = Smearing of slot walls

Appendix 1a: The principal characteristics of direct drilling grooves in a silt loam soil at moisture contents, 15%, 20%, and 27%.

(From Dixon, 1972)

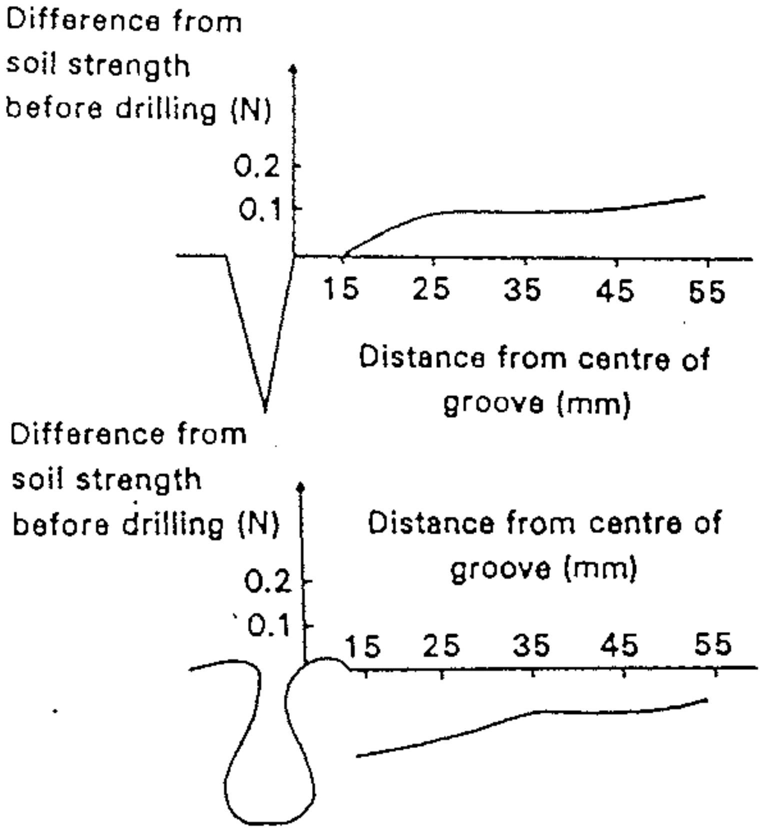


Fig. 1bi · Soil resistance at either side of triple disc (upper) and chisel coulter (lower) at 23% soil moisture content.

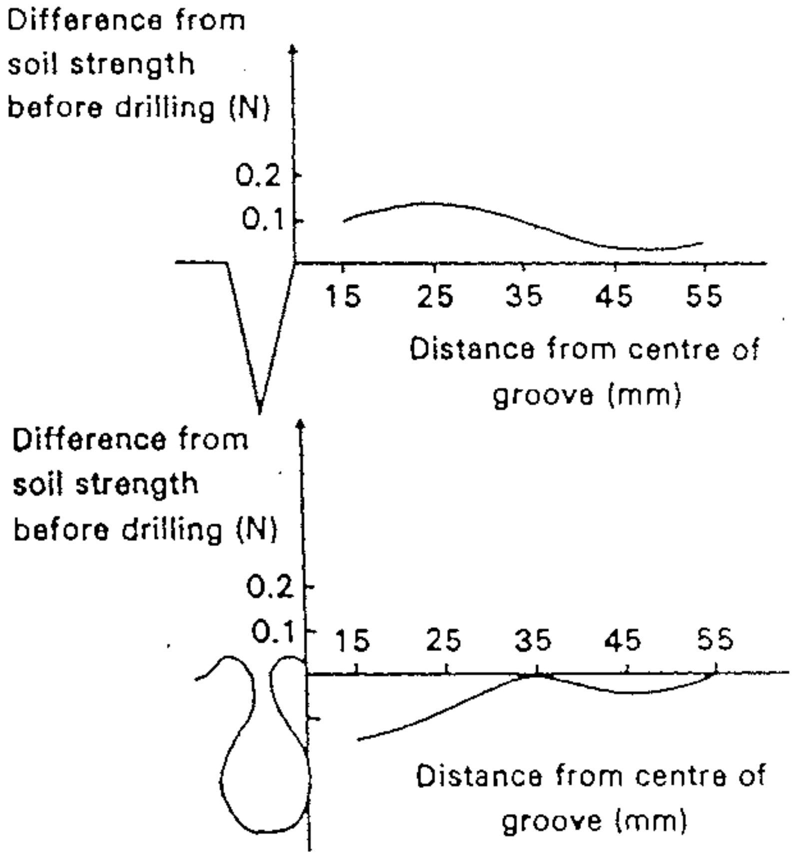
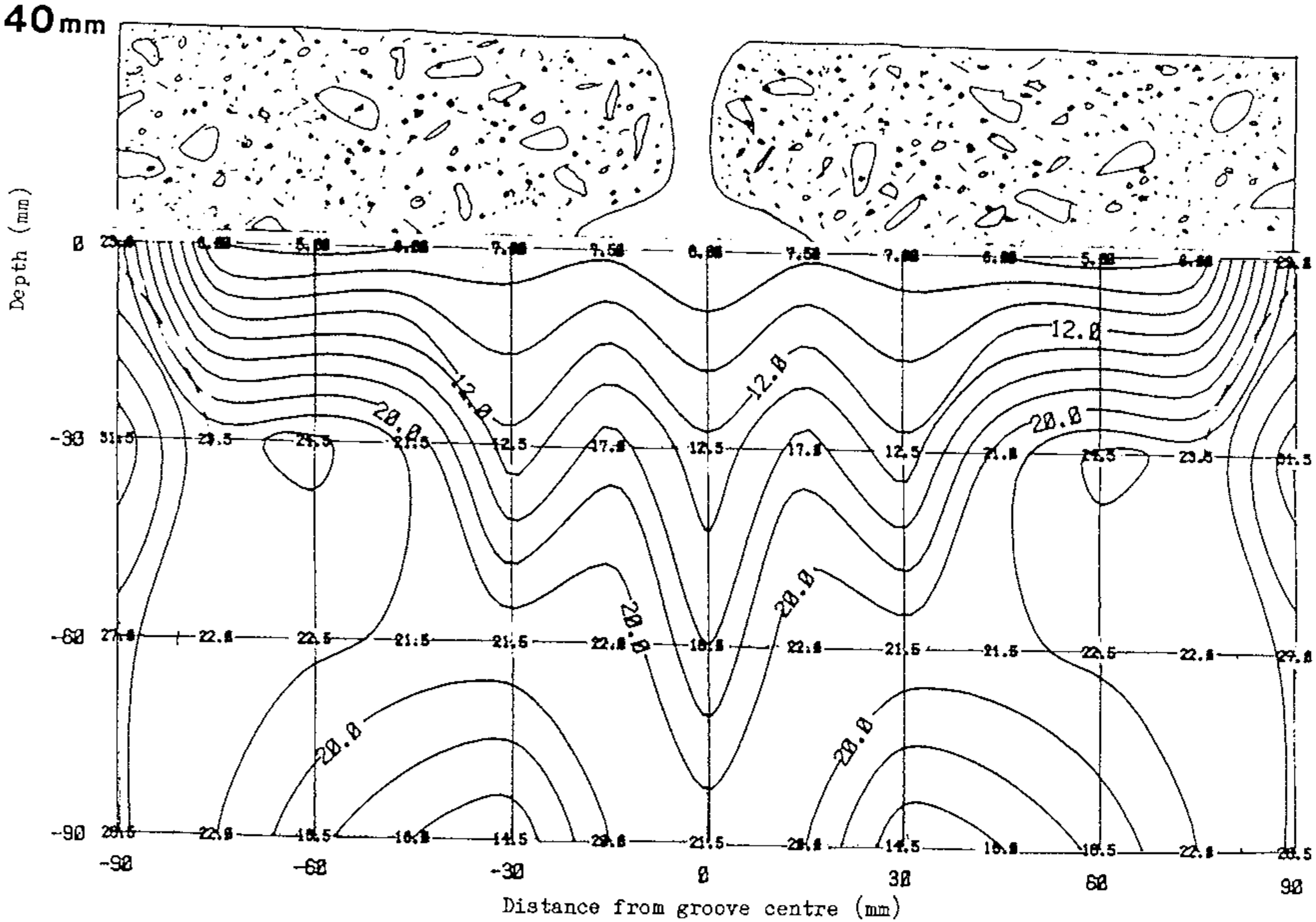
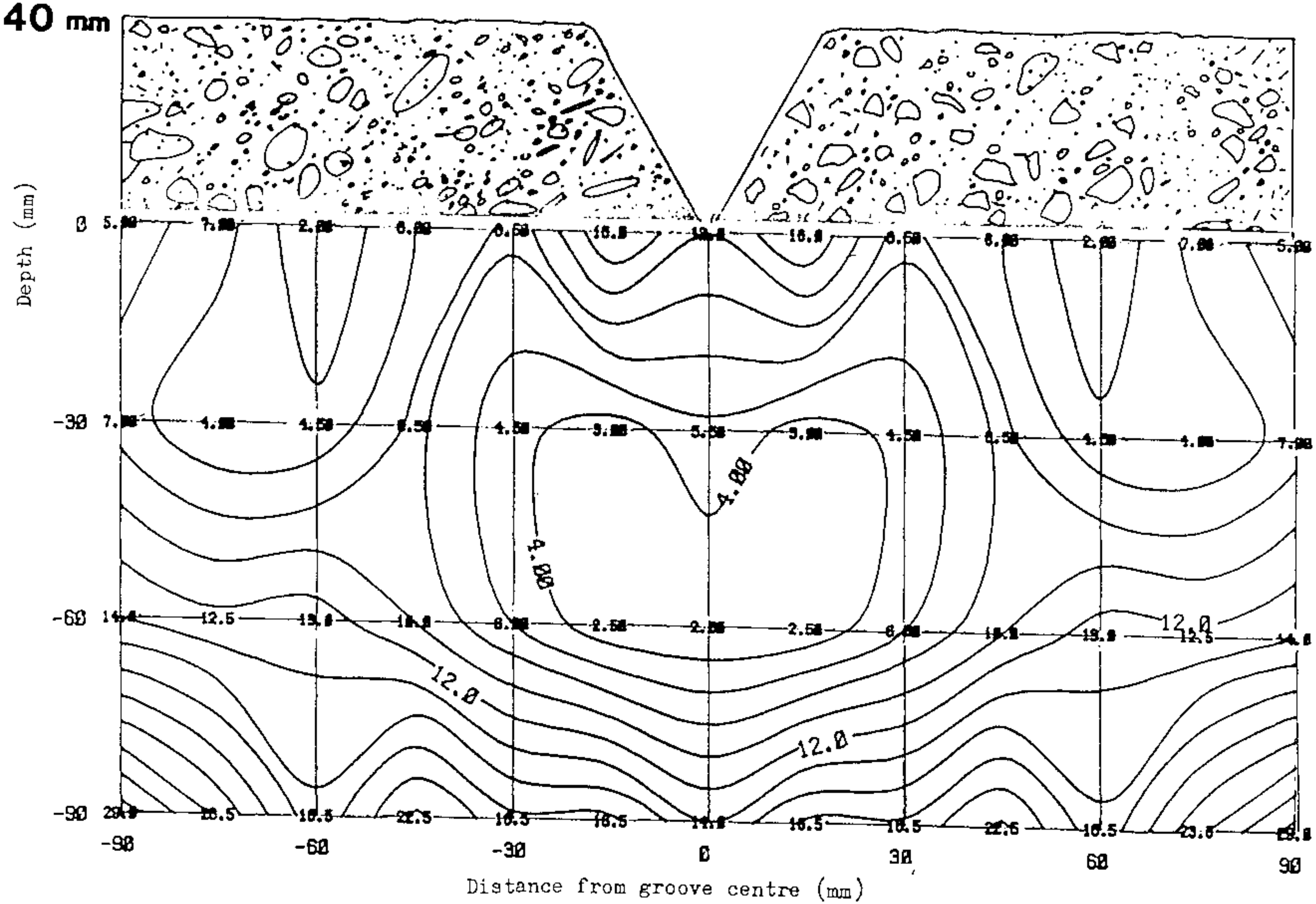


Fig.1b ii - Soil resistance at either side of triple disc (upper) and chisel coulter (lower) at 29% soil moisture content.

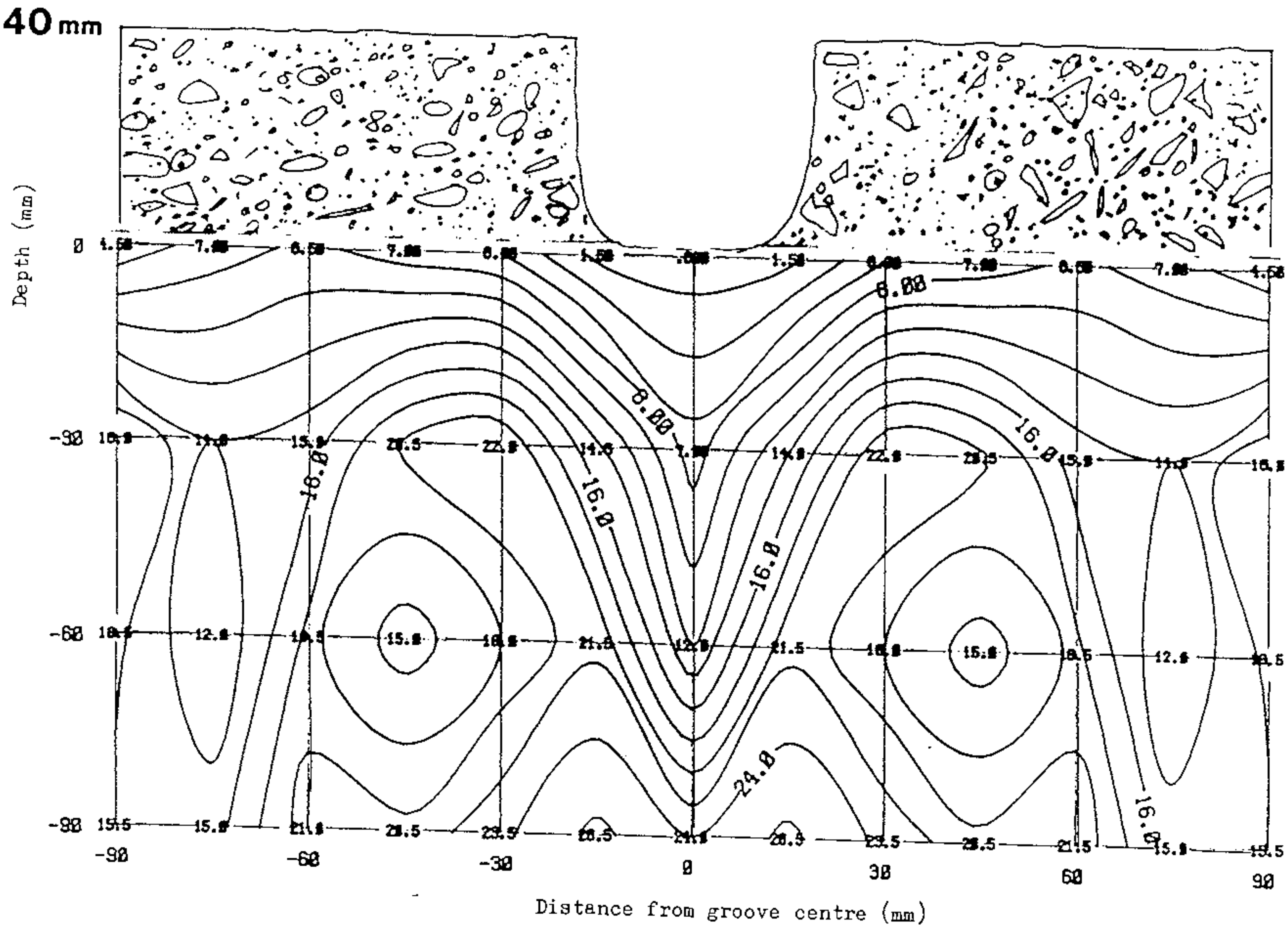
Appendix 1b: Limits of the effects of direct drilling opener types on soil resistance, from the centre of the grooves.
(From Mai, 1978).



Appendix 1ci: Iso-soil strength lines on either side of a direct drilled groove (Winged opener).
(From J. Mitchel, pers. comm, 1983).



Appendix 1cii: Iso-strength lines on either side of a direct drilled groove (Triple disc opener)
(From J. Mitchel, pers.comm, 1983).



Appendix 1ciii: Iso-strength lines on either side of a direct drilled groove (Hoe opener) (From J. Mitchel, pers comm, 1983).

Appendix 2a: Manawatu Soil and ambient temperatures during December, 1982 and January, 1983.

Date	Soil temperature at 10 cm depth (°C)		Ambient Temperatures (°C)			
	December	January	December		January	
			Max	Min	Max	Min
1	11.7	14.1	14.0	2.7	18.8	6.6
2	11.5	15.1	16.7	2.2	22.1	7.2
3	13.4	17.9	15.1	10.0	20.0	12.9
4	11.8	17.1	18.9	5.4	22.0	11.1
5	14.1	18.1	21.8	9.4	19.2	15.5
6	14.8	16.8	19.1	12.5	18.7	13.9
7	15.0	14.9	18.8	10.7	18.3	11.2
8	15.0	14.5	18.7	10.1	17.2	11.0
9	15.0	14.4	20.7	6.8	18.2	10.6
10	16.7	16.1	22.0	13.0	19.7	13.7
11	18.0	16.4	19.5	14.7	23.9	13.2
12	16.0	18.7	15.5	12.6	24.3	14.9
13	14.0	19.4	16.2	11.0	19.3	16.6
14	13.5	15.0	18.5	5.0	18.3	11.9
15	15.5	15.8	17.9	11.7	18.7	11.7
16	16.1	15.4	19.6	12.6	18.6	12.8
17	16.3	14.8	20.0	11.1	18.7	13.0
18	16.3	16.0	20.0	11.4	19.6	13.4
19	17.1	16.9	23.1	16.5	18.5	13.5
20	17.5	14.4	18.5	15.2	16.8	9.4
21	16.6	14.7	21.6	13.6	18.7	7.3
22	15.5	15.8	18.3	12.6	18.4	12.3
23	14.7	14.5	18.5	11.1	18.0	11.8
24	15.4	14.5	18.9	13.5	18.3	6.9
25	15.7	16.0	20.5	13.7	19.5	13.0
26	15.7	15.8	15.9	11.7	18.3	11.6
27	13.6	13.8	15.6	10.4	19.0	5.5
28	13.3	16.1	17.1	7.5	19.5	10.0
29	14.9	17.0	16.6	9.2	21.4	14.5
30	13.9	16.0	16.2	7.4	18.3	13.0
31	13.8	15.9	17.1	4.5	20.0	13.6
Average	14.9	15.9	18.4	10.3	19.4	11.7

Highest Max 23.1 °C 24.3 °C

Lowest Min 2.2 °C 6.6 °C

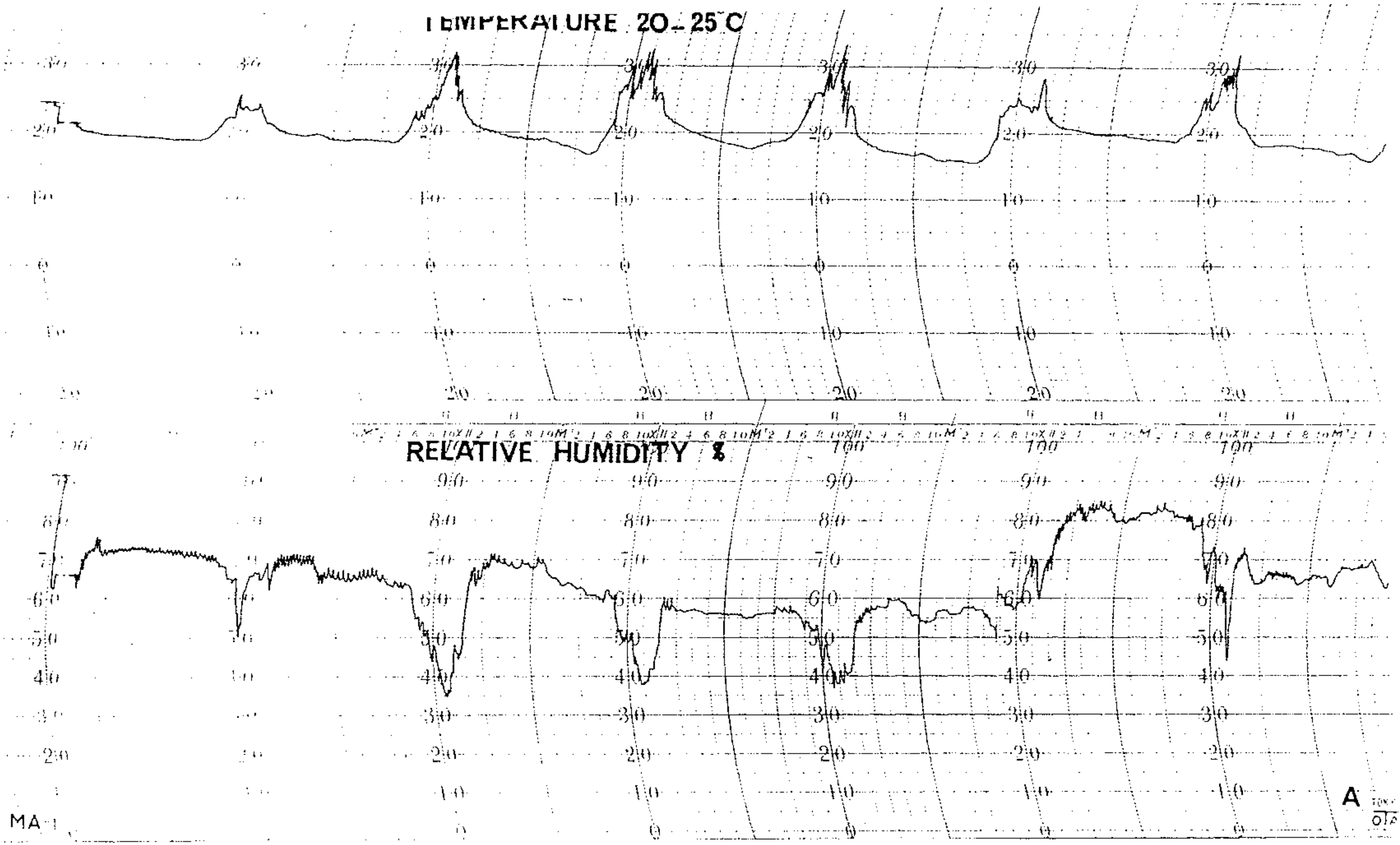
Source: Grassland Division, Department of Scientific and Industrial Research (DSIR), Palmerston North ,New Zealand.

Appendix 2b: Manawatu rainfall data (December, 1982; January, 1983)

Date	December, 1982		January, 1983	
	Rainfall (a) (mm)	Evaporation* (b) (mm)	Rainfall (a) (mm)	Evaporation* (b) (mm)
1	-	4.0	-	4.8
2	9.7	5.1	-	6.3
3	9.0	2.4	-	6.0
4	0.3	4.8	5.7	6.4
5	-	5.7	-	4.5
6	-	4.4	1.4 ***	2.7
7	-	6.9	-	5.1
8	-	10.0	-	6.0
9	-	4.0	-	3.5
10	8.0	0.0	-	1.5
11	33.4	6.8	-	3.0
12	0.6	12.4	6.6	4.6
13	0.3	4.5	7.6	4.6
14	-	5.2	2.1	8.1
15	-	2.6	5.1	6.2
16	-	4.0	-	6.0
17	- **	6.9	0.1	5.4
18	0.6	3.8	11.7	8.4
19	4.9	6.0	4.2	6.4
20	27.8	1.5	0.1	4.5
21	32.3	3.1	-	7.7
22	-	6.8	-	4.4
23	-	5.5	-	5.7
24	0.9	3.9	1.8	5.4
25	30.7	7.7	10.7	6.7
26	1.5	3.5	1.9	4.5
27	-	7.6	-	4.4
28	-	7.0	0.2	5.5
29	-	6.8	0.5	4.3
30	-	4.0	-	5.3
31	-	4.0	-	6.7
Total	160.0	160.9	59.7	164.2

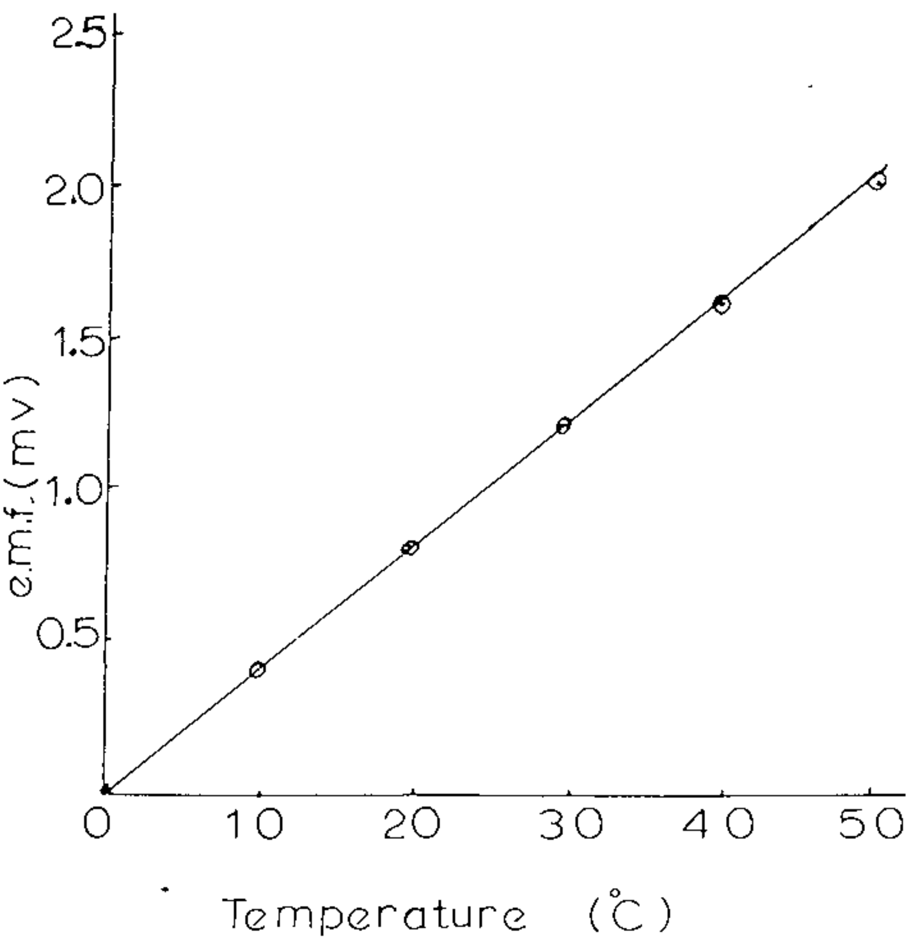
* From class A evaporation pan.
** Experiment started on December 17, 1982
*** Experiment terminated on January 6, 1983

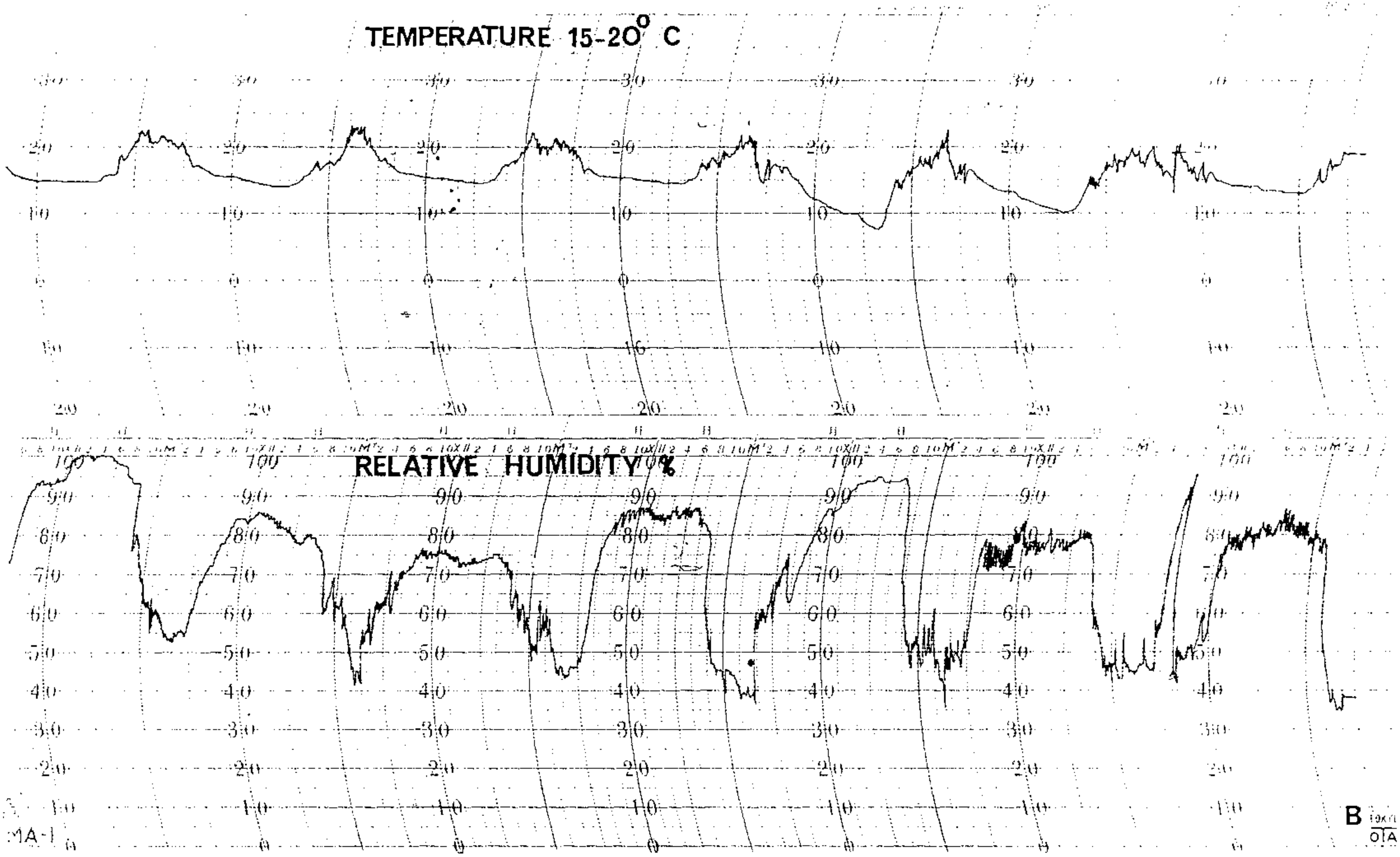
Source: Grassland Division, Department of Scientific and Industrial Research (DSIR), Palmerston North, New Zealand.



Appendix 3a: A sample of a weekly day/night temperature and relative humidity changes inside the glass house with a nominally controlled temperature range of 20-25° C.

Appendix 3b: Thermo-couple calibration curve.





Appendix 3c: A sample of weekly day/night temperature and relative humidity changes inside the glass house with a nominally controlled temperature range of 15–20° C.