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SEEDING DEPTH EFFECTS ON THE
PERFORMANCE OF WHEAT AND LUPIN
SEEDLINGS UNDER NO-TILLAGE

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ABSTRACT

The effects of seeding depth on the emergence and performance of many crops under a wide range of cultivated soil types and conditions have been well researched. The same effects under a no-tillage system are not nearly so well covered in the literature and the validity of extrapolation of results between different tillage systems has been shown to be dubious at best.

A field experiment was undertaken to compare the performance, in terms of various emergence parameters, of wheat (*Triticum aestivum* cv. Otane) and lupin (*Lupinus angustifolius*) sown at target depths of 20, 30, 50 and 70 mm into an untilled seedbed. A secondary aim was to assess the yield performance of wheat. The final factor involved was to assess the effect of the addition of disc scrapers to Cross Slot™ openers with respect to accuracy of seed placement. Emergence parameters assessed included total emergence, rates of emergence and time taken to attain both 5% and 95% emergence (of those seedlings that emerged).

Results showed that lupin tended to be planted deeper than wheat at any given opener depth setting and that the addition of scrapers had little, if any, effect either on the sowing depth achieved or on the variability of seed placement, by the opener, around the mean. Scrapers appeared to have very little consequential effect on any of the performance parameters measured, under the conditions of this experiment. The emergence parameters showed a reasonable linear response to increasing seeding depth, especially so in the case of lupin. The variability of total wheat emergence, in particular, at different depths was high compared with lupin. Lupin demonstrated a much higher degree of sensitivity than wheat for almost all emergence parameters. The exception to this was for rates of emergence where relative changes with depth were similar for both species. Fertile tiller numbers decreased with increasing depth at all four depths for wheat. However a high degree of variability in the yield data meant that yield was reduced only at the deepest (70mm) seeding depth. Regression analysis of day-of-emergence as a function of seeding depth of a large number of individual seeds indicated that seeding depth accounted directly for approximately half of the factors affecting day-of-emergence of both wheat and lupin seedlings. These results can be used as a basis for specifying design parameters for seed-drills with respect to the accuracy of depth control mechanisms.

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1. INTRODUCTION

Until recently man had for decades placed reliance on the mouldboard plough as the basis of cultivation systems for producing food from the land. This was done with a view to controlling weed growth and preparing what was considered to be an ideal seedbed to help promote maximum plant productivity. One event that firmly shifted attention towards a reduction in tillage was the advent of plant growth regulators, starting with 2,4-D, in the mid-1940's, with further selective and, later, non-selective herbicides following (Phillips, 1984a; Sprague, 1986). This eliminated, to a large extent, one of the major reasons for ploughing, namely weed control, resulting in a general reduction in tillage especially where such tillage had been used for post-emergence weed control.

The increasing importance of the no-tillage system to agriculture is indicated by the increasing area of land being farmed using no-tillage management. Annual survey results from the *No-Till Farmer* (Lessiter, 1992) showed that the total area under no-tillage in the USA increased from 1,349,863 ha in 1972 to 9,103,840 ha in 1992, an increase of 674%. This corresponded to an increase in no-tillage from 1.6% to 7.9% of the total area farmed in the USA. Data from the Conservation Technology Information Centre apparently suggest that this figure is closer to 10%, with a 67% rise between 1990 and 1992 (Mangold, 1992).

Rapid and even emergence of seedlings can be important in attaining maximum yields for a range of crops but may be influenced by the adverse effects of soil factors such as temperature, moisture, aeration and strength (Bowen, 1966; Currie, 1984). These factors, in turn, change with depth in the soil, indicating that seedling emergence and performance is dependent to some degree on seeding depth. The idea of manipulating seeding depth to try and optimise the conditions for germination and emergence applies, in principle, to both cultivated and untilled seedbeds. Untilled seedbeds, however, have tended to be less "forgiving" with respect to seed placement (Baker, 1976) and have also been reported to contain inherent physical obstacles to accurate seed placement that are not present in cultivated seedbeds.

Reports by Choudhary et al. (1985), Ritchie (1982) and Wilkins et al. (1983) have clearly shown that differences exist between the range of no-tillage seed-drill openers with respect to their seeding distribution patterns, with large variations in seeding depth often resulting in poor seedling emergence, even under favourable growth conditions. The majority of the work reported in the literature relating seeding depth

to emergence, however, has been carried out in cultivated soils, with only a few referring to untilled soils.

The uneven soil surface encountered in no-tillage, combined with the possibility of planting at shallower depths to optimise soil temperature conditions (Gupta et al., 1988), means that accuracy of depth of seed placement has become a more important design criterion for no-tillage seed drills than it has been in the past for conventional seed drills. This suggested the need to investigate further, the effects of depth variations in seeding on the emergence and yield of plants in an untilled soil as a possible pointer to how accurately a seed drill might need to place seed at a given target depth in order to minimise effects on emergence and/or yield.

The objectives of this study were to highlight possible machine design parameters which affect variations in planting depth. The aim was to obtain an assessment of the amount of variability in seeding depth that might be allowable in a seed drill without impacting significantly on crop performance in terms of germination, emergence and yield.

2. LITERATURE REVIEW

2.1 The advantages and disadvantages of no-tillage

As outlined above, the last few decades have seen a marked increase in the area of land under no-tillage management systems. A definition of no-tillage (or direct drilling) suggested by Phillips et al. (1980) was of a crop planting system involving either a complete absence of tillage or, alternatively, just sufficient tillage to place the seed and cover it with soil to allow for adequate germination and emergence.

Tillage, or the lack of it, has the ability to affect just about every aspect of crop production. This has had flow-on effects on short-term profitability and long-term productivity (Sprague, 1986). Crosson et al. (1986) pointed out that, although most farmers wanted to conserve soil and water, based on capitalistic principles it was economics that would ultimately dictate the extent to which no-tillage was accepted as a viable alternative to cultivation.

2.1.1 Advantages

The potential catastrophic results of continuing unabated soil erosion in terms of lost productivity and pollution of waterways are well documented (Crosson, 1985; Foster and Moldenhauer, 1985; Walker et al., 1987). It has been generally accepted that retention of surface residues is the most effective method of reducing soil erosion by both water (Laflen et al., 1981; Mannering and Meyer, 1963; Meyer et al., 1970) and wind (Fryrear, 1985; Siddoway et al., 1965; Skidmore, 1988).

The relationship between no-tillage and high levels of surface residue (Colvin et al., 1981) meant that results seemed to almost invariably indicate considerable reductions in erosion where no-tillage methods were used (Laflen and Colvin, 1981; Lal, 1976; McGregor et al., 1975; Mutchler and Greer, 1984; van Doren et al., 1984). Reductions in soil erosion by wind of a similar order to those for water erosion have also been obtained, as evidenced by results of a number of experiments conducted by N.P. Woodruff in Ohio, cited by Unger and Jones (1989).

As an example, Phillips et al. (1980) cited L. L. Harold and W. M. Edwards who studied three watersheds in Ohio growing corn under poor management practices (cultivation up and down the slope), improved management practices (cultivating on

the contour) and no-tillage practices, with respective land slopes of 6.6%, 5.8% and 20.7%. During a severe rainstorm of 175mm over seven hours, soil losses were said to be 51,477, 7,307 and 72 kg/ha for the respective watersheds - a clear illustration of the potential benefits of no-tillage.

Tillage and residue both affect soil water regimes by affecting evaporation, surface ponding, runoff, infiltration, capillary movement of water through the soil and the trapping and holding of snow on the soil surface. However research has tended to produce variable results for combinations of the two factors with little progress made in improving soil moisture conservation until more recent times (Saxton et al., 1988).

Finer, less aggregated cultivated soils were reported to be more susceptible to the formation of a surface seal due to the impact of raindrops (Epstein and Grant, 1971). The most widely accepted method for overcoming this problem of soil crust formation has been the use of crop residues, preferably managed as a surface mulch (Army et al., 1961; Lattanzi et al., 1974; Mannering and Meyer, 1963; Lal et al., 1980; Lal, 1985; Saxton et al., 1988). This has also been linked to greater soil aggregation due to higher levels of organic matter (OM) in the surface layers of soils under no-tillage (Carter et al., 1990; Gallaher and Ferrer, 1987; Hamblin, 1984).

Although untilled soils have been reported as exhibiting either similar or lower bulk densities than cultivated soils, particularly in tropical regions (e.g. Lal, 1976), the most common scenario has been for there to be increases in soil bulk density and decreases in total porosity in untilled soils (Gantzer and Blake, 1978; Carter et al., 1990). Even with higher bulk densities, untilled soils have often shown higher infiltration rates (Edwards, 1982). Many authors have linked this fact to the size distribution and/or continuity of pores under no-tillage compared with cultivated soils (Klute, 1982; Edwards, 1982; Ehlers, 1975; Lal and van Doren, 1990). A number of those same authors specifically mentioned the contribution of earthworms, found in greater numbers under no-tillage (e.g. Deibert et al., 1991), towards this greater number of continuous, larger pores.

Evaporation has been considered to be a major component of water loss from the soil (Linden, 1982) accounting for up to 50-70% of annual precipitation in dryland areas (Papendick and Campbell, 1988). Crop residue mulches have been widely studied as a means of reducing evaporation (Unger, 1990), with major effects showing up in reductions in first stage evaporation (Bond and Willis, 1969, 1970, 1971; Unger and Parker, 1976) when the soil surface is wet.

The changes in infiltration and evaporation under no-tillage outlined above suggests that total soil moisture should be greater under no-tillage than under conventional cultivation. This has been confirmed by many reports in the literature (Berry et al., 1987; Blevins et al., 1971; Carefoot et al., 1990; Munawar et al., 1990; Zhai et al., 1990).

Many reports have also indicated the general trend for lower average soil temperatures under crop residues (Army et al., 1961; Gupta et al., 1983; Lindwall and Erbach, 1983; Nyborg and Malhi, 1989). Where ambient temperatures were high, the presence of residue could act to reduce seed zone soil temperatures to a level that would result in improved seed and seedling performance (Abrecht and Bristow, 1990; Lal, 1978; McCown et al., 1981).

Agriculture has, in recent decades, become more energy intensive, with approximately 80% of the energy used in US agriculture coming from fossil fuels such as petroleum and natural gas (Phillips et al., 1980). Crosson et al. (1986) cited estimates of fuel savings under no-tillage, compared with plough cultivation, of between 50 and 75%. A similar range was covered by the results of Allen et al. (1975) and Phillips et al. (1980) who found savings of around 55% and 80%, respectively. Hughes (1975) suggested that savings might have been greater than 90% on a silt loam soil under New Zealand conditions. Many authors have also indicated total energy savings for no-tillage, including such factors as nitrogenous fertiliser inputs and the energy costs of machinery (Crosson et al., 1986; Frye, 1984; Patterson et al., 1980; Phillips et al., 1980; Wittmus et al., 1975) as well as savings in terms of labour inputs (Crosson et al., 1986; Frengley, 1983).

Crop yields had the potential to increase under certain conditions with no-tillage according to Allen et al. (1975), Herbek et al. (1986), Lindstrom and Forcella (1988), Maurya (1986), Norwood et al. (1990) and Wolf and Edmiston (1989). Even on soils high in clay content Morrison et al. (1990) found that "contrary to some claims" use of the appropriate technology could result in similar or better yields for no-tillage compared with the more usual chisel tillage on these soils in Texas. Cotton lint yield was as much as 42% higher with no-tillage than with conventional tillage in one year.

2.1.2 Disadvantages

The increase in soil moisture under no-tillage, and the associated decreases in soil temperature, can have some negative effects under certain conditions. In cooler climates this has been associated with reduced crop growth and/or yields of spring-sown crops (Allmaras et al., 1964; Kaspar et al., 1990; Mock and Erbach, 1977). The general trend with respect to temperature effects on germination and emergence (covered in more detail later in this review) has been for increasing speed of both with increases in temperature, within certain limits (Alessi and Power, 1971; de Jong and Best, 1979). This suggests that emergence of crops under no-tillage could be delayed compared with those on cultivated soils (Al-Darby and Lowery, 1987; Johnson and Lowery, 1985) although this problem has been shown to be surmountable by more accurate, shallower planting of seeds (Gupta et al., 1988; Lindwall and Erbach, 1983).

Most researchers seem to be in general agreement that the situation where no-tillage has most commonly produced consistently lower yields than conventional cultivation has been where the land in question tended to be quite flat and the soil had poor internal drainage tendencies. A number of reviews of the literature pertaining to comparative yields on different soil types and under differing climatic conditions bear this general consensus out (Blevins, 1984; Cannell, 1985; Crosson et al., 1986; Griffith et al., 1986; Phillips et al., 1980; Prasad and Power, 1992; van Doren et al., 1976).

It is perhaps a moot point whether or not weeds can be considered to be a greater problem with no-tillage than with conventional cultivation. The biggest difference has been that rather than relying on cultivation, no-tillage has relied on herbicides to kill established plants and to prevent the establishment of further weeds from seed sources in the soil (Triplett and Worsham, 1986). A number of reports were cited by Witt (1984) to illustrate the fact that acceptable weed control could be attained with herbicides in no-tillage over a wide range of crops. Triplett and Worsham (1986) stated that the continued improvement in herbicides and their management systems had meant better control of perennial weeds that had previously been a problem.

No-tillage has been reported to alter the soil fauna balance, compared with conventional cultivation, in terms of numbers and/or distribution (Edwards, 1975; House and Parmalee, 1985; Winter et al., 1990) by reducing the physical destructive effects that intensive cultivation had on the habitat of soil inhabiting insects, as well as non-insect pests such as slugs and mice (All and Musick, 1986). Follas (1982) cited

numerous reports that were said to allude to a general increase in pest problems under no-tillage with slugs appearing to be of particular concern in no-tillage in New Zealand.

Similarly, diseases have also appeared to be more prevalent under reduced tillage conditions with surface residues providing an environment suitable for the survival, growth and multiplication of plant pathogens, particularly fungal and bacterial pathogens (Boosalis et al., 1986; Elliot and Lynch, 1984; Frederickson et al., 1987). Severe outbreaks have been shown to be more likely under cool, moist conditions (Boosalis et al., 1986; Cook and Haglund, 1991). Complex crop / pest / environment interactions have affected whether or not both pests (All and Musick, 1986) and diseases were a problem under no-tillage. In any case, potential problems were considered controllable with appropriate management (Phillips, 1984b).

Changes in the soil biosphere have been shown to lead to changes in the way plants take up nutrients from the soil as well as having an effect on the amount of nutrient available (particularly nitrogen) via changes in such factors as mineralisation, denitrification, immobilisation and C:N ratios (Aulakh et al., 1984; Babowicz et al., 1985; Power and Doran, 1988; Power et al., 1986; Rice and Smith, 1984; Thompson, 1992). Changes in these factors have often resulted in a reduction in available N, especially in the first few years after changing to no-tillage, and especially on moist, cool, poorly-drained soils where the potential existed for large denitrification losses (Fox and Bandel, 1986).

Possible problems with water contamination, particularly from pesticides, have been another area of potential concern with no-tillage. Felsot et al. (1988) claimed that, because no-tillage did not provide the facility for incorporation of either fertilisers or herbicides into the soil, this could lead to the possibility of greater concentrations in runoff soon after application. A review of literature by Crosson et al. (1986) suggested that use of pesticides (particularly herbicides) generally increased under no-tillage compared with cultivation, although there are differing opinions on this point (Little, 1987).

Reports in the literature from Felsot et al., (1988), Hallberg (1986) Logan et al., (1989) and Goss (1989) also point to disagreement over whether pesticide and/or nitrate leaching has been higher or lower under no-tillage. Despite this lack of agreement, it was suggested that one way to ensure that the contribution of no-tillage to water pollution was kept to an absolute minimum was to adopt current

management practices and develop new strategies that maximised utilisation of nitrogenous fertiliser and minimised pesticide inputs into the no-tillage system (Felsot et al., 1988; Lal et al., 1988).

2.2 Biological performance of seed-drill openers with no-tillage

Buften (1984) suggested that the role of drill opener assemblies in the seed/soil relationship was extremely important, insofar as efficient use of the ambient soil conditions by well designed openers was likely to encourage good seed germination and emergence. Various reports have indicated that different no-tillage opener designs have produced quite different results in terms of crop establishment over a range of climatic and soil conditions (Baker, 1976; Baker et al., 1988; Chaudhry, 1985; Chaudhry and Baker, 1988; Choudhary and Baker, 1980, 1981a, b; Baker and Mai, 1982; Tessier et al., 1991a, b; Ward et al., 1991; Wilkins et al., 1983) making it important to try and establish the strengths and weaknesses of individual opener designs from a biological viewpoint.

Major factors that were seen to have an effect on crop establishment via their influence over the seed/ soil environment were listed by Choudhary (1985) as vegetation competition control, seed groove shape, seed depth control, crop residue handling, fertiliser placement and pest management, with the interrelationships between many of these also noted. Baker (1976) had earlier shown that, of these biological variables affected by opener design, slot shape and cover over the seed zone (in the form of both soil and crop residues) were the most important, at least in dry soils.

Slot shapes produced by no-tillage openers have been generally classified into three broad categories: "V"-shaped, "U"-shaped and "inverted T"-shaped (Baker, 1976). The "V"-shaped slot has usually been formed by a twin inclined disc arrangement characteristic of double and triple disc openers, while the "U"-shaped slot could be formed by a range of openers, from simple hoe coulters through flat angled discs and dished discs to power-till openers. The "inverted T"-shaped slot was the result of more recent research starting with a so-called "chisel" opener (Baker, 1976), which had resulted in the development of a Cross Slot™ opener (Baker and Saxton, 1988).

Earlier forms of this opener, also resulting in an "inverted-T" slot, were also referred to as "winged" openers.

2.2.1 Soil moisture

The focus of attention when studying moisture generally lies at the extremes of the scale, i.e. in very dry conditions and in very wet conditions. Choudhary (1985) suggested that groove shape would be of little significance under ideal conditions and Erbach (1981) cited work by Kalmbacher which apparently showed that opener type made little difference when establishing legumes into killed pasture as long as competition was controlled and water and fertiliser levels were adequate. Contrary to this, work by Saxton in the USA has apparently suggested that, even under optimum moisture conditions at seeding, the "inverted-T" slot can produce superior yields compared with other slot shapes, despite there being no difference in the plant populations established (C.J. Baker, pers. comm., 1993).

-Dry soils

Research by Baker (1976) indicated that the amount and degree of cover over sown seeds was of considerable importance with respect to germination and sub-surface seedling survival in dry soils. "U"-shaped slot formation, with its associated soil disturbance, has usually resulted in a supply of loose soil that could be used to cover the seed (Baker, 1976; Baker and Choudhary, 1988; Tessier et al., 1991b) although this was often not the case in high clay soils (Ward et al., 1991). The formation of "V"-shaped slots was, in contrast, normally associated with downwards and outwards compression of the soil (Mai, 1978), often resulting in little or no loose material that could be used as a covering medium except in lighter, sandier soils (Ward et al., 1991). In the case of the "inverted-T" slot the two residue-covered soil flaps on either side of the central disc were reported to be lifted upwards and outwards and then pressed back into place by the following press wheels, resulting in almost complete soil and residue cover over the seed (Baker and Choudhary, 1988).

Baker (1976) and Choudhary and Baker (1980, 1981a, b, 1982) have reported that germination might be poor in "U"-shaped slots even with good soil cover due to inadequate seed-to-soil contact, whereas "V"-shaped slots might produce good germination because the seed was wedged in the base of the slot. These same authors

also showed that final emergence in "V"-shaped slots was often poor under drying conditions due to a lack of cover that resulted in seedling desiccation.

Tillage bin experiments carried out under partly or fully controlled climatic conditions (Baker, 1976; Choudhary and Baker, 1980; 1981a, b) showed the "inverted-T" slot to have a significant advantage over "U"- and "V"-shaped slots (hoe and triple disc opener, respectively) in terms of wheat seedling emergence under dry soil conditions. In the case of Choudhary and Baker (1980), with the soil near permanent wilting point, emergence from "inverted-T"-, "U"- and "V"-shaped slots was 58.4%, 31.3% and 10.5%, respectively. This was linked by later experiments (Choudhary and Baker, 1981a, b) to the ability of a particular slot shape to retain vapour phase moisture (described as the "moisture vapour potential captivity" - MVPC). Results from these experiments and from subsequent research (Choudhary and Baker, 1982) showed that high, medium and low MVPC values, respectively, could be expected from "inverted-T", "U"- and "V"-shaped slots.

-Wet soils

Several reports originating from Massey University have emphasised the differences in biological performance of several different opener types under wet soil conditions (Baker et al., 1987, 1988; Chaudhry, 1985; Chaudhry and Baker, 1988; Chaudhry et al., 1987). The results of Baker et al. (1988), Chaudhry et al. (1987) and Chaudhry and Baker (1988) indicated that "winged" ("inverted-T") and hoe ("U") openers gave superior performance with respect to a number of factors, including greater numbers of emerged seedlings and earthworms, higher root and shoot weights and a greater oxygen diffusion rate (ODR) in the soil immediately surrounding the slot.

The benefits of earthworms was illustrated in the operation of some openers with the "winged" and hoe openers producing almost three times more seedling emergence in the presence of earthworms than without earthworms (Baker et al., 1988). From their results, Baker et al. (1988) concluded that the way in which seed and seedling performance responded to different opener types and residue conditions in a wet soil was affected mainly by residue and opener effects on ODR, earthworm activity and bulk density in the immediate seed zone; factors which had been shown to have a high degree of interdependence. They further stated that the biological risks involved with no-tillage could be reduced by paying close attention to slot shape and the placement of surface residues.

2.2.2 Soil compaction/smearing

According to Klepper et al. (1987), pre-emergent root growth was important in terms of the supply of water and oxygen, so that any soil strength effects that reduced the size of these roots and/or their ability to extract water and oxygen from the soil matrix surrounding the slot would obviously have a related effect on time to emergence. Baker (1976) suggested that localised compaction in no-tillage opener grooves would be of importance only if the initially moist soil subsequently dried out, thus impeding the passage of roots from the germinating seed into the surrounding soil.

Dixon (1972), in his investigation of opener effects on soil compaction, showed that smearing of the slot wall was dependent on moisture content of the soil as well as opener type. Both hoe and triple disc openers created extensive zones of smearing on the slot walls in moist conditions (27% moisture content) with the triple disc opener also creating compacted zones both around the sidewalls and at the base of the slot. The "chisel" opener used to create an "inverted-T" slot in this trial produced no compaction or smearing in the immediate seed zone. Under drier soil conditions even the triple disc opener did not appear to cause unduly high levels of smearing or compaction. These effects were confirmed by Baker and Desborough (1985) in Australia and in the case of the triple disc and "chisel" openers, by other studies (Baker and Mai, 1982; Choudhary and Baker 1981a; Mai, 1978).

2.2.3 Fertiliser placement

The placement of fertiliser in close proximity to the seed (in the same slot) has been shown to cause problems in terms of germination and emergence. Klepper et al. (1987) cited P.E. Rasmussen who apparently found that high osmotic pressures in the soil solution in close proximity to the seed, due to the use of too much starter fertiliser, caused a reduction in the emergence of wheat seedlings. This was in agreement with Hegarty (1984), although Baker and Afzal (1986) suggested that high moisture vapour potential in an inverted T slot may have offset these same detrimental effects of fertiliser on osmotic potentials in their no-tillage experiment, at least in dry soils.

This suggests the need to consider the question of the amount of separation that might be required between seed and fertiliser to offset any detrimental effects. Payton et al. (1985) concluded that seed/fertiliser separation of at least 50mm was required (at a

rate of 112 kg/ha N) to avoid adverse effects on emergence. Similar results were obtained by Babowicz et al.(1985) using three high analysis nitrogenous fertilisers.

The nature of the "V"-shaped slot has made it difficult to separate seed and fertiliser if placed in the same slot, necessitating the use of extra openers to deep band fertiliser if it was required (Hyde et al., 1987). The same authors raised the possibility of using a double disc seed opener preceded by a hoe opener solely for deep banding fertiliser.

Of the types of openers that form "U"-shaped slots the most suitable for adaptation to separation of seed and fertiliser (at least in the vertical plane) has been the hoe opener in its various forms (Hyde et al., 1987; Payton et al., 1985; Wilkins et al., 1983, 1987). This type of unit was reported to first deposit fertiliser (often in liquid form) which was then covered with firmed soil by a baffle arrangement, with the seed being deposited immediately behind the baffle on top of the layer of firmed soil. The success of this type of modification has been found to be dependent on operating speed and soil moisture levels, with seed sometimes dropping into the deeper fertiliser furrow in wet soils (Payton et al., 1985).

According to Baker and Saxton (1988), the "inverted-T" slot formed by the Cross Slot™ opener provided for horizontal separation of the seed and fertiliser by about 20mm, a separation that remains consistent regardless of speed or soil moisture levels. The claim that the separation achieved by this opener was adequate to prevent seedling damage was confirmed by trials carried out on barley and fodder radish by Choudhary et al. (1988). This horizontal separation was found to be at least as effective as vertical separation and, in the case of drier soils and where separation was reduced to 10mm, horizontal separation appeared to be slightly superior to vertical separation in terms of promoting rape seedling emergence (Baker and Afzal, 1986).

Baker and Afzal (1986) suggested that the reason for the success of this opener, which had a smaller degree of separation than other reports had suggested necessary, lay in its design, in that the central disc component cut a slit approximately 75mm deeper than the two horizontal ledges upon which the seed and fertiliser were placed. In no-tillage situations this slit remained quite evident, possibly forming an effective barrier to lateral solute movement from the fertiliser towards the seed, a theory that was backed up by results from tilled soil (in which the central slit was seen to collapse) which showed greater seedling damage than in the untilled soil.

2.2.4 Residue management

It is difficult to identify which biological factor micro-management of the residue by openers impinges most directly on. Certainly the problem of allelopathic effects of toxins produced from decomposing residues or from microorganisms using residue as an energy source has been identified by Elliot and Lynch (1984) and Stroo et al. (1988). However, Baker and Choudhary (1988) claimed that the role of micro-management of residues in trapping vapour phase moisture was even more important, besides which, effective separation of the seed and residue in the slot eliminated allelopathic effects (Baker et al., 1987).

Plant residue on the soil surface has adversely affected most soil engaging tools and the placement of chemicals and seed on or into the ground (Erbach et al., 1983). This suggests that one important design parameter of a no-tillage opener should be to manage surface residue to gain maximum benefit in terms of the seed microenvironment while also acting to minimise the risk of physical machine blockages, allowing for accurate seed placement (Baker and Saxton, 1988; Koronka, 1973; Hyde et al., 1987). This problem of trading off residue handling capacity against biological considerations can lead to design conflicts, but it was suggested by Baker and Choudhary (1988) that where this was the case, "...residue handling characteristics of the openers should not take priority over the biological tolerance of such openers."

Hoe-type openers with their rigid shanks have been more susceptible to residue buildup problems than rolling discs. Residue could bend around the shank especially without the use of a disc coulter preceding it, particularly on narrow-row grain drills, unless lateral clearance was gained by staggering openers on two or more ranks (Fowler, 1990; Erbach et al., 1983; Allen, 1988). Hoe openers also tended to push the residue to one side so that the residue was not maintained strictly over the drill slot (Baker and Desborough, 1985), as did dished discs and flat angled discs.

Probably the biggest problem associated with triple and double disc openers with respect to residue has been a phenomenon known as "hairpinning". This occurred when a piece of straw was not cut by the disc opener but was pushed, doubled-up, into the drill slot (Chaudhry, 1985; Hyde et al., 1987; Chaudhry and Baker, 1988). This could prevent seed-to-soil contact, reducing the chance of germination in dry soils. In wetter soils the residue-seed contact could reduce germination and growth of seedlings due to phytotoxic effects from the decaying residue. Double and triple

disc openers also tended to force the remaining residue aside as they create their seed groove.

The Cross Slot™ opener, referred to previously, appeared to successfully plant through a variety of residue conditions while maintaining a virtually complete soil and residue cover over the seed, which was deposited in an "inverted-T" slot (Baker et al., 1979; Baker and Saxton, 1988; Baker and Choudhary, 1988). Baker et al. (1979) suggested that the trash handling capability of this opener was one of its most satisfactory features. The opener consisted of a central scalloped disc with symmetrical winged shanks located on each side of the disc. When in the soil the leading edge of these shanks was held against the disc by soil forces, preventing trash from forcing its way between the two components. The disc had the effect of directing all uncut residue underneath the path of the stationary winged shanks. The effect of this opener has been to leave the residue in almost exactly the same position as it was before drilling, while giving the seed the best possible microenvironment for survival (Baker and Choudhary, 1988).

2.2.5 Pests

The general problems of soil pests in no-tillage have already been referred to. Very little research appears to have been conducted into the effects of different openers on insect damage. Follas (1982) presented results for a comprehensive study of the differences between "V"-, "U"- and "inverted-T" shaped slots with regard to their respective propensities for slug infestation. In both wet and dry soils no significant differences showed up between the openers in terms of either slug ingress into the drill slot or slug damage to the seeds or seedlings, although the author suggested that experimental design faults may have clouded the results. Baker (1976) had earlier suggested that the "inverted-T" slot could be more susceptible to slug damage because it protected the seed from drying out. Follas (1982) found no evidence of this in his study but did note that he also found no measurable differences in the microenvironment within the different slots either.

2.3 Seed placement considerations

It has long been accepted that good crop establishment is an important prerequisite to the attainment of acceptable yields. Bleasdale (1984) cited the "Parable of the Sower", St Luke, chapter 8 to indicate this early recognition of the fact that if seed was smothered by weeds or eaten by birds, or if it was sown into compacted or dry ground, or sown in the wrong place, then failure to establish the required crop would be the likely result.

The primary aim of crop production has been to maximise photosynthesis (Stoskopf, 1981). Thus modern producers have obviously been keen to ensure that their crops emerged and began photosynthesising as soon as possible after planting. This establishment phase, which is an important part of the crop cycle since it determines the plant population from which the eventual yield will be derived, could be affected by seed and soil factors both during germination and during the growth of the seedling through the covering layer of soil (Perry, 1984). These same soil factors could also affect later plant growth through effects on root growth and uptake of water and nutrients by those roots.

This soil physical environment, as it directly affected the pre-emergent seedling and plant roots, has been described in terms of four main factors; soil temperature, soil aeration, soil impedance/strength and soil moisture (Bowen, 1966; Currie, 1984; Letey, 1985). Other soil physical properties such as bulk density, aggregation, organic matter content and pore size distribution could be considered as indirect factors since their effect on crops was through their effect on the four main factors mentioned previously (Letey, 1985).

According to Stoskopf (1981), seedling emergence, particularly, depended not only on seedling vigour, but also on seeding depth because of the likelihood of differences in these soil physical factors being encountered at different depths. The idea of manipulating seeding depth to try and optimise the aforementioned conditions for germination and emergence has applied, in principle, to both cultivated and no-tillage seedbeds although no-tillage has presented inherent physical obstacles to accurate seed placement that were not present in cultivated seedbeds. Many authors have pointed out the depth control problems associated with rougher surfaces and/or high levels of surface residues found in no-tillage systems (Bauer and Kucera, 1978; Berry and Mallett, 1988; Erbach et al., 1983; Mock and Erbach, 1977; Unger, 1986). Combined with the likelihood of having to plant shallower in no-tillage (Gupta et al.,

1988), this suggests an increasing importance on drill design parameters pertaining to accuracy of seeding depth.

The increase in soil moisture levels under no-tillage have substantially reduced the likelihood of having to plant deeper to ensure that the seed was placed in soil with adequate moisture for germination. Baker (1976) suggested that crop residue retained over the seed zone helped to maintain high in-groove soil moisture in dry soils resulting in improved survival and emergence. This, along with further studies (Choudhary and Baker, 1981a,b; Choudhary and Baker, 1982), suggested that successful establishment of shallow seeded crops under dry soil conditions would be more likely using direct-drilling than using conventional cultivation, especially if an opener type was used that was capable of maintaining complete residue cover over the drill groove and, thus, high levels of humidity.

Results from Hughes and Mitchel (1987) indicated that cereal cultivars selected to perform well in cultivated soils might also have been expected to perform well in no-tillage situations. These authors concluded that overcoming the engineering problems associated with preparation of the seedling environment in no-tillage was more important than trying to improve results through plant breeding. The idea of concentrating on depth control was also suggested by the results from Choudhary et al. (1985), which showed a high negative correlation coefficient between depth variation and emergence of peas and fodder radish under no-tillage conditions. This concept was also supported by Ritchie (1982) and Wilkins et al. (1983).

2.3.1 The effect of soil factors on germination and emergence

The theory of seedling emergence revolves around the uptake of moisture by the seed under suitable temperature and oxygen conditions which, in turn, produces root and shoot growth through the soil resulting in the eventual emergence of the seedling. In practice, under field conditions, both the seed and seedling may have been subjected to a variety of environmental stresses prior to emergence (Hegarty, 1984). Because of the interactive effect of many of the stress factors, it has been suggested that these factors should be considered as a whole rather than individually to enable a more complete understanding of the problems which may occur in the field (Perry, 1984; Hegarty, 1984). Stoskopf (1981) suggested that research on the subject seemed to indicate some difficulty in specifying conclusively which one factor had the greatest effect.

Much of the literature dealing with these soil factor effects on seeds and seedlings refers to tilled seedbed conditions. Reports such as those by Baker (1976) and Choudhary and Baker (1982) have questioned the validity of extrapolating results obtained in tilled seedbeds to untilled situations. Both Baker (1976) and Perry (1984) suggested that untilled seedbeds were likely to be less tolerant of variability in seeding depth than tilled seedbeds.

2.3.1.1 Moisture

Seed germination could, according to Klepper et al. (1987), be divided into three distinct stages; imbibition, enzyme activation and emergence of the radicle from the seed, with moisture being required for the first and third stages. A good supply of water was necessary for rapid germination, with most field crops starting to germinate when their moisture content reaches 26-75% (Martin et al., 1976). This supports the common belief that it was liquid phase moisture in the soil that was largely responsible for seed imbibition, although Perry (1984) cited work by P.C. Owen which apparently indicated that wheat could absorb sufficient vapour phase moisture to germinate at a relative humidity of 98% and a temperature of 20°C.

Soil moisture also affected the growth after germination with emergence in wheat, for instance, resulting from elongation of cells in the coleoptile due to water pressure-induced enlargement (Klepper et al., 1987). In a study of wheat, gram and barley seedling emergence in a layered cultivated soil (dry soil over wet soil), Gill and Prihar (1989) showed that where seeds were placed in contact with moist soil at the dry soil/wet soil interface, both the rate of emergence and total percentage emergence were superior to a situation where the seeds were placed 2 cm above the dry soil/wet soil interface. Similar findings were obtained in cultivated soils by Wilkins et al. (1983) who found that six different grain drill openers produced differing wheat seedling emergence rates and that the most critical factor affecting these was the ability of each opener to place the seed in contact with soil that contained sufficient liquid phase moisture.

The supply of moisture to seeds in soil was said to be governed by factors such as hydraulic conductivity, soil matric potential, osmotic potential and the contact area between seed and soil (Collis-George and Hector, 1966). This was supported by Lindstrom et al. (1976) and Parker and Taylor (1965) who described a progressive decrease in emergence rate with decreases in soil water potential (down to the limits

of -1000 and -500kPa, respectively). In apparent contrast to this, the results of Lafond and Fowler (1989a, b) suggest that soil moisture levels ranging from field capacity to permanent wilting point had no significant effect on the speed of either germination or emergence of winter wheat.

2.3.1.2 Aeration

Aeration has been defined by Currie (1984) as the "dynamic interaction between the soil and the combined respiratory processes in the soil, i.e. of seeds, roots, other soil flora and fauna". Since the atmosphere is the sink from which all the oxygen must be derived, good aeration must involve a continuous network of air-filled pores between soil and atmosphere, although Currie (1984) also suggested that characterisation of aeration solely in terms of air-filled porosity was an oversimplification of the situation.

The availability of oxygen has been shown to affect both the germination and emergence of seeds/seedlings (Martin et al., 1976; Klepper et al. 1987). Both the second stage (increased metabolic activity) and the third stage (protrusion of the radicle from the seed) of germination, as described by Klepper et al. (1987), require oxygen to proceed, with relatively large quantities being involved (Martin et al., 1976). Increases in metabolic activity in the germinating seed has resulted in greatly increased oxygen demand, the supply of which could be greatly restricted by excess soil moisture in waterlogged soils (Klepper et al., 1987; Hegarty, 1984).

Lack of oxygen in the soil has also resulted from impedance of diffusion of oxygen between the atmosphere and the soil (Hegarty, 1984) and competition due to microbial respiration, especially under conditions that were close to limiting (Perry, 1984). As well as this, indirect effects have resulted from the production of toxins such as acetic acid under anaerobic conditions (Lynch, 1978) and from soil-borne pathogens under the same conditions (Cook and Murray, 1987).

As mentioned previously, studies carried out to relate the effect of different no-tillage openers on germination and emergence of barley in wet soils (Chaudhry, 1985; Chaudhry et al., 1987; Chaudhry and Baker, 1988; Baker et al., 1988), have also highlighted the importance of the oxygen diffusion rate (ODR) regime surrounding the seed zone for maximising seedling emergence. It was suggested that, in these wet soils, the oxygen regime in the seed zone was the most important soil-environmental factor affecting seedling performance (Baker et al., 1988).

2.3.1.3 Strength/impedance

It has been suggested that soil strength is the edaphic factor most likely to influence the emergence of the seedling after germination, as opposed to the influence of other factors on the germination process itself (Benjamin, 1990). Apart from indirect effects on water and oxygen availability which could affect germination and emergence through reduced porosity and/or increased bulk density, the physical state of the soil could also directly affect emergence by impeding the growth of both the coleoptile and roots of the pre-emergent seedling (Perry, 1984; Klepper et al., 1987). These authors considered that the effect on shoot growth was probably the more important of the two at this stage of development since, until the emergent shoot could begin photosynthesising, the seedling was entirely dependent upon the reserves of energy contained in the seed to sustain growth. In the case of wheat, at least, coleoptile elongation was more affected than root elongation under identical conditions of soil strength (Collis-George and Yoganathan, 1985a,b) although negative effects on roots might also affect coleoptiles through reduced water uptake (Klepper et al., 1987).

In a tilled seedbed, one of the biggest problems facing the pre-emergent shoot has been the likelihood of encountering a soil crust, especially on structurally unstable soils and/or where the soil had been excessively pulverised during tillage (Currie, 1984; Perry, 1984). This aspect tended not to be such a problem under no-tillage where the presence of surface residues provided distinct benefits in terms of the prevention of surface crust formation (as detailed earlier in this review) although, conversely, higher bulk densities under no-tillage, especially in temperate regions, have led to higher mechanical impedance (as much as 15 times greater than in tilled soils) in the overall soil mass under certain moisture conditions (Ball and O'Sullivan, 1982). In general, soil strength has tended to increase with decreasing moisture and increasing clay content (Arndt, 1965; Brock, 1973; Currie, 1984), although increases in organic matter in the soil, as occurred with no-tillage, may have decreased soil strength (Currie, 1984).

Monocotyledonous and dicotyledonous plants were said to be likely to differ widely in their abilities to emerge from deeper plantings in higher strength soils (Parker and Taylor, 1965). White and Robson (1989) investigated the effects of high strength soil (in the form of a soil crust) on emergence of lupin, wheat peas and medics. Emergence of seedlings with epigeal germination was reduced by the presence of a crust, with the effect being severe on medics and on the smaller-seeded lupin, *L.*

angustifolius. The larger-seeded *L. albus* was not affected to quite the same degree. In contrast to these epigeal seedlings, emergence of wheat (monocotyledon) and peas (hypogeal, dicotyledon) was unaffected by the presence of the high strength soil crust. It was also noted that sowing lupins deeper added to the problem of emergence. These results closely follow the trends reported by Morton and Buchele (1960) who stated that emergence energy requirements of a seedling increased directly with a range of factors including depth, soil strength and the diameter of the 'mechanical' seedling that they used. Another example of the relationship between soil strength and emergence is illustrated by the results of Addae et al. (1991), who found that two cultivars of wheat showed an inverse correlation between soil strength and percent emergence.

2.3.1.4 Temperature

The literature abounds with reports of the effects of temperature on germination and emergence of a variety of crops - among them, winter wheat (Burleigh et al., 1965; Dubetz et al., 1962; Lafond and Fowler, 1989a,b; Lindstrom et al., 1976; Russelle and Bolton, 1980), spring wheat (Addae and Pearson, 1992; Addae et al., 1991; Hucl and Baker, 1990), barley (Radford, 1987; Russelle and Bolton, 1980) maize (Abrecht and Bristow, 1990; Alessi and Power, 1971; Lindwall and Erbach, 1983), cotton (Bowen, 1966) and sorghum (Parker and Taylor, 1965). The general trend of the results has indicated decreasing time for germination and emergence with increasing temperature, within certain temperature limits.

Lafond and Fowler (1989a), for instance, showed that both the rate of kernel water uptake and the speed of germination of winter wheat were greatly affected by temperature changes in the range 5-30°C, with median germination time decreasing from 6.9 days at 5°C to 0.9 days at 25 and 30°C. An attendant study (Lafond and Fowler, 1989b) investigating the emergence of winter wheat showed similar trends, with median emergence time decreasing by 1.3 days for each degree increase in soil temperature in the range 5-20°C. A contemporaneous improvement in the uniformity of emergence was also noted in this case. These results for emergence are in general agreement with those obtained by Lindstrom et al. (1976) with their winter wheat emergence prediction model.

In terms of total (percent) emergence, temperature appears to have a much lesser effect than on rates of emergence. Dubetz et al. (1962) found that, although emergence rates of barley and wheat increased as the temperature increased in the range 6-24°C, total emergence was not affected for either species. Similar findings were presented for wheat by Addae and Pearson (1992), in the temperature range 5-25°C, and by Addae et al. (1991), in the temperature range 5-17°C.

This soil temperature factor has been of particular interest in no-tillage because of the fact that mean soil temperatures have tended to be lower under no-tillage regimes than under conventional tillage, due mainly to the presence of a surface mulch which affected heat and water flow characteristics as well as altering the reflectance and absorption of incoming solar radiation (Benoit and Lindstrom, 1987; Unger and McCalla, 1980). Another factor to consider is that not only are soil temperatures often lower under no-tillage, but the extent of diurnal fluctuations in temperature is usually reduced also (Aston and Fischer, 1986).

2.3.2 Agronomic implications of seeding depth

2.3.2.1 Seeding depth vs emergence

The result of all the previously mentioned soil factors combined has been that the performance of seeds/seedlings, in terms of emergence, has differed according to the depth at which they have been planted (Jafari and Fornstrom, 1972). The optimum sowing depth for any crop was likely to depend upon factors such as soil and climatic conditions at the time of planting, which could make it difficult to determine what that appropriate depth might be (Perry, 1984; Radford, 1986). In any case, Perry (1984) felt that it should not be any deeper than was necessary to provide appropriate conditions for germination and emergence in terms of moisture and soil cover.

The reason most often quoted for deeper planting of seeds, in dryland areas, has been the requirement to place the seed into direct contact with moist soil to assist with germination (Abrecht, 1989; de Jong and Best, 1979; Hart, 1964; Radford, 1987; Radford and Wildermuth, 1987). Deeper seed placement in the search for moisture has often resulted merely in a shift of the problem from being one of poor germination to one of poor emergence with coleoptiles of cereals, for instance, having often ruptured below the surface when planted too deeply (Sunderman, 1964). Kaufmann (1968) also suggested that barley seedlings with shorter coleoptiles that did emerge

from deeper plantings tended to have severely etiolated leaves. Other authors have suggested that to overcome this problem either plant varieties with longer coleoptiles may be selected (Radford 1987; Sunderman, 1964), or effective planting depth should be reduced by forming a well-defined furrow over the drill row to reduce the actual depth of soil through which the coleoptile has to pass before emergence (Abrecht, 1989; Radford, 1987).

It should be noted that results and recommendations with respect to coleoptile length have differed in the literature. An example is the result of Kaufmann (1968) who found, using four varieties of each crop, that seedling emergence was related to coleoptile length in the case of barley, but not in the case of either wheat or oats. Photiades and Hadjichristodoulou (1984) also found in their study in Cyprus that barley was more sensitive to seeding depth than was wheat. This, however, conflicts with data obtained by Radford et al. (1989) and Gill and Prihar (1989) both of whom indicated that wheat was, in fact, more sensitive than barley to depth of sowing. It appears, though, that coleoptile length has played a part in determining the ability of many cereal cultivar seedlings to emerge, especially from greater depths (Burleigh et al., 1965; Radford, 1987).

As stated earlier, accurate seed placement could be used to help overcome the problem of lower temperatures in no-tillage soils, with Gupta et al. (1988) and Lindwall and Erbach (1983) both suggesting that the effect of cooler temperatures on corn emergence under no-tillage could be compensated for by reducing planting depth. The latter authors also noted, however, that under no-tillage conditions uniform depth control of planters was much more difficult, especially when planting at shallow depths of around 3-5 cm.

With no-tillage winter wheat production, it has been shown that good establishment of the crop before the onset of winter was essential to reduce the risk of the wheat crowns being exposed to suboptimal temperatures, even under the insulating blanket of snow trapped by the no-tillage stubble (Lafond and Fowler, 1989b; Klepper et al., 1987). Studies of the interactive effects of temperature, moisture and seeding depth have suggested that, rather than waiting for precipitation, it was better for farmers to plant no-tillage winter wheat at a shallow depth (10-25 mm) at the optimum seeding date even if this meant seeding into a dry seedbed (Lafond and Fowler, 1989b; Loepky et al., 1989).

The results of many other authors, the majority of whom have carried out their trials on cultivated seedbeds, have stressed the importance of seeding depth with respect to the establishment of a wide range of crops. Seeding depth effects on wheat establishment have been reported by Burleigh et al. (1965), Gill and Prihar (1989), Goodman and Scott (1985), Hadjichristodoulou et al. (1977), Hart (1964), Hucl and Baker (1990), Lindstrom et al. (1976) and Photiades and Hadjichristodoulou (1984), with the general trend being for a reduction in emergence rate and, often, total emergence with increased seeding depth.

Experiments carried out by Gill and Prihar (1989) followed this trend when moisture was non-limiting but it was noted that, where moisture was a limiting factor, slightly deeper planting (7-9 cm) produced better emergence than either shallower (3-5 cm) or deeper (11-13 cm) planting. Morrison (1989), in a study using no-tillage on a clay soil in Texas, found that increasing depth led to slight improvement in emergence of wheat (at depths of 24, 54 and 83 mm). Sorghum and cotton, on the other hand, showed significant improvements in emergence as depth was decreased.

Barley has also been extensively studied with respect to seeding depth, both in conjunction with similar work on wheat (Gill and Prihar, 1989; Hadjichristodoulou et al., 1977; Hart, 1964; Photiades and Hadjichristodoulou, 1984) and also separately (Radford and Wildermuth, 1987; Roebuck and Trenerry, 1978; Sepaskhah and Raessi Ardekani, 1978). In those studies where wheat and barley were considered together, similar trends in results to those obtained with wheat (outlined previously) were also obtained with barley in each case.

Radford and Wildermuth (1987) and Sepaskhah and Raessi Ardekani (1978) both reported barley emergence rates decreasing as depth increased. The latter trial also showed decreases in total emergence with increasing depth (in the range 20-120 mm). Trials carried out in England (Roebuck and Trenerry, 1978) indicated that deeper sowing (60-75 mm vs. 25-35 mm) affected spring barley by delaying emergence as well as reducing percentage establishment, plant heights and fertile tiller population. This last factor was compensated for by increases in grain size and weight with final yields being similar in all the trials except for one, where a badly panned seedbed resulted in deeper sowing causing a 27% decrease in yield.

2.3.2.2 Overall crop performance

Many of the studies mentioned previously have carried on to assess the effects, if any, that seeding depth might have had on final yield as well as on emergence. Another way to assess seeding depth / yield effects is to link the seeding depth / emergence results to the results of other studies that have attempted to establish a correlation between emergence variations and yields. Both of these approaches can provide an indicator of the validity of proposing a link between seeding depth and final yield, even though the latter is a somewhat indirect and, perhaps, more tenuous approach. The complexity of the situation regarding evenness of emergence versus yield was indicated by Bleasdale (1984), who stated: ".....I have long been intrigued by the fact that two groups of competing plants, which at an early stage of growth are of a similar weight per unit area, can give very different yields at some later harvest; and by the paradox that, when the early weights per unit area are very different, it is often probable that final yields will be identical."

An example of results showing decreased yield with increased seeding depth is given by Hadjichristodoulou et al. (1977) who found that establishment and plant vigour were adversely affected by deep seeding of cereals under field conditions in Cyprus, and that an adverse flow-on effect was evident in various agronomic characteristics measured, including grain yield. This trend of decreasing yield was mostly reflected by a fall in plant establishment with increasing depth, however there were occasions where differences in yield were not associated with significant differences in plant population, indicating that other factors associated with seeding depth might have had an influence on the final yield. Later trials conducted along similar lines (Photiades and Hadjichristodoulou, 1984) produced similar trends for both wheat and barley.

The influence of seeding depth on yield and survival of no-tillage winter wheat was investigated at 14 different locations in Saskatchewan, Canada by Loeppky et al. (1989). The target seeding depths were 10-25 mm (shallow) and 25-50 mm (deep), with actual measured depths showing considerable variation between locations. Yields were unobtainable from five sites due to severe winterkill while at two out of three sites where moderate winterkill occurred slightly greater numbers of plants survived at the shallower depth, resulting in higher yields. At four of the other six sites where virtually no winterkill occurred at either seeding depth, yields were significantly greater (11%, on average) in the shallow seeded plots. For example, at one site where winter survival was 99% for both shallow and deep seeding, the yields obtained were 3.6 and 3.4 t/ha, respectively. In six out of nine trials where yields

were obtainable, shallower seeding produced significantly higher yields, whereas deeper seeding never produced a yield advantage. Four out of the six trials that escaped serious winter injury showed similar trends, indicating that this yield advantage with shallower seeding was not due solely to improved winter survival. In these trials, as was the case with the results of Hadjichristodoulou et al. (1977) and Photiades and Hadjichristodoulou (1984), the number of heads produced per unit area appeared to be the most important agronomic factor related to the reduction in grain yield.

Another indication that depth of seeding could affect yield, independent of total population establishment effects, was given in an unpublished report from the University of Saskatchewan (cited by Stoskopf, 1981) which detailed spring wheat production over a four year period. Averaged over four years, plant populations established from seeding depths of 5.1 and 7.6 cm depths were identical but yield from 7.6 cm depth was approximately 10% lower than that from 5.1 cm depth.

Other reports have found no differences in yields for various cereal crops planted at different depths (Hart, 1964; Roebuck and Trenerry, 1978; Lindwall and Erbach, 1983; Frederick and Marshall, 1985) with at least one report indicating greater yields from deeper seeding (Roth et al., 1984). In the case of Roth et al. (1984), winter wheat showed greater yields from 38 mm seeding depth compared with 19 mm at five out of six locations where seeding depth effects on yield were significant. The authors suggested that shallower seeding could cause plants to form crowns near the soil surface, resulting in a greater degree of susceptibility to frost heaving and lodging, an explanation also proposed earlier by Stickler (1962).

It is generally accepted that an increase in plant density in cereal crops, as with many other crops, leads to an increase in total dry matter production up until some population threshold is reached, whereupon no further increase is possible under a given set of conditions. Grain yield, however, tends to reach a peak (the length or flatness of which will differ between species) with any increase above a certain population density leading eventually to a decrease in grain yield. Evidence of this can be found for a number of cereal crops such as wheat (Hampton, 1981; Hampton et al., 1981; Withers and Pringle, 1981; Auld et al., 1983; Anderson, 1986), barley (Kirby, 1967; Millner, 1983), sorghum (Martin and Kelleher, 1984; Wade and Douglas, 1990) and maize (Dungan et al., 1958; Eagles, 1987).

Perry (1984) noted that it was sometimes argued from this type of evidence that, because of compensatory growth, it was not important how many seedlings were established above a set minimum. However, he went on, to make an important point: ".....the circumstances of a seed rate trial where the seed-bed is carefully prepared and the crop well tended to allow maximum opportunity for compensation to occur differs from those in which seeds have been subjected to suboptimum environments resulting in low populations. Not only have seeds and seedlings been killed, but those that have emerged will have been exposed to stress and hence unable to achieve their full yield potential. Furthermore, the soil environmental conditions which adversely affected establishment may persist to limit root and plant growth." He went on to cite work from Perry and Harrison that investigated grain yields of deteriorated barley seeds sown in adverse (very wet) conditions. The results from this trial apparently showed that plants which survived the adverse soil conditions were not able to compensate for lower populations despite a greater number of fertile tillers per plant and grains per ear.

Another important factor that requires some consideration is the effect of uneven emergence on productivity within a plant population. Benjamin (1990) suggested that relative time of seedling emergence had a considerable bearing on later productivity especially, based on the limited evidence available, in the case of monocultures and that the importance of this relationship had yet to be fully recognised. He also suggested that, although many causes existed for differing emergence times, the importance of these pre-emergence processes in terms of effects on productivity in monocultures was based solely around their influence on time to emergence. It was noted, however, that this hypothesis needed to be subjected to further experimental verification.

There is no doubt that later emerging plants within a population of 'normal' density have been permanently disadvantaged in terms of later growth due to competition from neighbouring, earlier emerging plants (Knight, 1983; Soento and Donald, 1980). In this latter study using barley the authors found that later emerging plants produced fewer grains than those that emerged earlier. On medium density (normal commercial sowing rate) drilled plots the slope of the regression of grain numbers on emergence was such that a three day delay in emergence resulted in a 43% reduction in the number of grains formed. Due to differences in competition this reduction was somewhat less in square planted plots at the same density (approximately 25%). The date of emergence was considered to be influenced by seed size, seeding depth and soil environmental conditions.

Other authors have investigated this effect of delayed and/or uneven emergence on yields. Graven and Carter (1990), for instance, found that delayed emergence of a number of corn hybrids (as a result of cold soil conditions) was associated in all cases with slower early growth and delayed silking and also often resulted in reduced grain yield. Nafziger et al. (1991) hand planted corn on three different dates to obtain various different combinations of within- and between-row variability. These results again indicated that uneven emergence would be likely to result in reduced yield although the authors suggested that to justify replanting of the crop, at least 25% of the plants would have to be delayed by 3 weeks or more.

In his review of the effect of variations in time of emergence on plant growth and development Benjamin (1990) found that emergence variations appeared to be a major source of variation in mature plant weight, most probably because these variations in emergence caused plant sizes to differ at the time when competition for growth resources commenced. It was also suggested that: "Time of seedling emergence has its largest effect when spread is large, when seedlings have a high relative growth rate (warm, moist conditions and fast-growing species), when between-plant competition is intense (at high plant densities), and when harvests are made not long after seedling establishment".

It is, however, by no means certain that any stresses applied to the seed and seedling prior to emergence will necessarily show through as effects on yield in all cases. This can be shown by studies of the relationship between yields and seed vigour, as a comparative example. A comprehensive review of this relationship by TeKrony and Egli (1991) included a section on grain crops (i.e. where the crop is harvested at full reproductive maturity) which looked at 25 references covering 9 species. In 17 of these cases, where plant density did not influence yield, it was apparently suggested that there was no relationship between seed vigour and yield, in this case of grain harvest at full reproductive maturity. Most of the remaining references apparently showed a significant decrease in yield with decreasing seed vigour, however in all the cases cited this was said to be associated with the establishment of sub-optimal plant populations as well. Thus, problems with stresses imposed on the seed appear more likely to show through in yields at lower plant populations rather than at higher populations, although TeKrony and Egli (1991) also suggested that this relationship between seed vigour and yield appeared to hold true for later than optimum crop planting dates at optimum densities as well.

2.3.3 Depth control in no-tillage

2.3.3.1 The problems associated with no-tillage

The difficulties of maintaining even depth of seeding in various conservation tillage environments (including no-tillage) compared with conventionally cultivated seedbeds have already been alluded to. Erbach (1981) and Koronka (1973) both suggested that penetration of openers, in general, was a major stumbling block to achieving accurate seed placement in no-tillage conditions. Erbach et al. (1983) suggested that crop residue, in particular, could produce inconsistent seed placement by interfering with depth gauging and also by hindering the penetration of the opener where residue levels were high. The latter problem has been especially evident with the use of double or triple disc openers (Erbach et al., 1983; Payton et al., 1985).

Increased soil strength under no-tillage has also played a part in causing penetration problems (Lindwall and Anderson, 1977). This has been especially so for double disc and triple disc openers (Schaaf et al., 1981), a tendency explained by Hyde et al. (1987) who stated that, whereas disc openers relied on the weight of the machine to force them into the ground, hoe and shank type openers were at least partly reliant for penetration on shape and draft forces. The latter situation has also held true for the cross-slot opener (Baker and Saxton, 1988). The fact that penetration forces for triple disc and double disc openers, especially, increased substantially with depth was also illustrated by Hyde et al. (1987). They cited the example of a "Yielder" triple disc drill that used every third opener to deep band fertiliser between twin rows of seed planted at a shallower depth. Figures showed a downforce requirement of between 4415 and 10791 N for the deeper openers compared with 442-647 N for the seed openers.

The results of Mock and Erbach (1977) showed quite variable seed depth placement in conservation tillage plots compared with ploughed plots. These authors stated that; "This decreased uniformity probably resulted from interference of plant residue on the soil surface with the operation of the planter. Also, the depth gauging devices of conventional planters are not sufficiently sensitive to follow the uneven soil surface condition common to some conservation-tillage systems." Unger (1986) also suggested that less effective seed placement was the cause of the lower corn plant populations that were found on plots with high residue levels in his experiment. The micro-relief of field surfaces covered in both wheat and sorghum stubble was characterised by Morrison and Gerik (1985b) with both crops showing variations

within a range up to 40 mm above the soil surface, although wheat stubble produced higher frequency undulations than sorghum stubble.

Other authors have also touched on the inability of openers to accurately place seed at the set depth, even in relatively homogeneous cultivated soils. Özmerzi (1986) carried out tests in a soil bin on four opener types - single disc, double disc, hoe and shoe openers - and found that the ratio of mean sowing depth to actual coulter working depth varied between 40 and 89%, with coefficients of variation of between 3 and 17% for sowing depth distribution. Choudhary and Baker (1980) and Choudhary et al. (1985) showed that different no-tillage opener types produced differing degrees of depth variation, with openers that produced a high level of variation in seeding depth tending to produce lower seedling emergence.

Four types of no-tillage opener, with and without dual side-mounted depth control wheels, were assessed for accuracy of seed placement by Campbell (1985) using lupin and barley. Increasing speed from 6 to 12 km/hr reduced seeding depth for barley but apparently not for lupin. Inconsistencies in emergence also indicated that each crop responded differently to changes in forward speed. Although a target depth of 40 mm was attempted for barley, results of field trials suggested that this was rarely achieved especially with the openers without wheels, which were more difficult to maintain at a set depth. The fact that seeding depth and not opener type was causing the differences in emergence was confirmed by a covariate analysis for the barley trials.

Buften (1984), Patterson (1984) and Ritchie (1982) have all suggested that the actual depth at which the seed was deposited was dependent not only on the dynamics of the opener, but also on factors such as variations in both release position and the trajectory followed by the seed in free flight, and displacement of seeds on impact with the soil.

2.3.3.2 Depth control mechanisms

Most early suggestions for improvement in depth control for conservation tillage planters have generally revolved around adaptations of existing planting machinery - mainly to overcome the residue problem - with the most common alteration being the addition of some form of rolling coulter in front of the opener (Erbach et al., 1983), an improvement which was shown to improve the uniformity of seed placement in the presence of high levels of residue (Allen et al., 1975). This adaptation along with the

addition of weight to the drill, especially triple disc drills (Hyde et al., 1987), was aimed mainly at coping with one aspect of the improvement to the accuracy of seeding depth, i.e. the problem of penetration.

Morrison (1988a) described depth control systems for planting equipment as an interaction between the vertical forces applied to the opener and the reactive forces of the depth gauging mechanism, with these latter mechanisms having to support any excess vertical forces not required by the opener. The author listed the possible sources of these downforces as the weight of the opener, added ballast (including the weight of any seed and fertiliser) and any force applied via compression or tension mechanisms. Ballast could be in the form of weights attached to individual openers or to the drill frame itself and was used when insufficient weight was provided by the drill. The depth gauging options that were available to control the degree of penetration were the other part of the overall depth control equation.

-Downpressure systems

Downpressure systems on individual openers have been traditionally supplied by spring systems attached between the drill frame and the opener. The non-linear behaviour of these springs has resulted in fluctuating downforces on the opener due to expansion and compression of the springs as the opener followed the ground contour, leading to differing depths of penetration (Morrison, 1988b). Because of this non-linear behaviour springs were not considered the ideal solution to obtaining constant downpressure, with very long heavy duty springs being required to minimise the effects of this non-linearity (Baker and Saxton, 1988). The availability of some constant force spring systems was noted by Morrison (1988b), however the author stated that these systems had not been taken up by any of the major manufacturers at that point in time. This has led to the development of alternative methods of providing downforce via pneumatic (Morrison, 1988a) or hydraulic (Baker and Saxton, 1988; Hyde et al., 1987; Morrison, 1988b) systems where each opener was controlled by a hydraulic ram or air shock absorber.

An example of a hydraulic system has been provided in conjunction with the Cross Slot™ opener (Baker and Saxton, 1988). This system uses a double acting ram on each opener with pressure supplied from a nitrogen-cushioned reservoir. Because of the random vertical movement of the openers there was said to be very little change in the volume in the reservoir, resulting in almost constant downforce. These same rams

also provided the means to lift the openers into the transport position. Even if the openers were lifted from the soil while working (e.g. turning) a patented "memory valve" restored the previous operating pressure once the openers were lowered again. The maximum downforce able to be applied to individual openers was stated as being around 3434 N (350 kg) which, it was suggested, might be necessary in some hard no-tillage soils.

-Depth gauging options

In producing a guideline for the selection of seeding equipment for use in conservation tillage conditions, Morrison et al. (1988) listed six options for controlling the depth of seeding. These were as follows:

1. Rear press wheel.
2. Side gauge wheel.
3. Skid plate.
4. Front wheels and rear press wheels tandemed.
5. Frame lifting / gauge wheels.
6. Depth band.
 - a. Bands on front leading coulter.
 - b. Bands on disc opener.

Erbach (1981) cited a 1978 design by D.C.Erbach that used a walking beam arrangement to link front wheels and rear press wheels (each placed 7.5 cm longitudinally from the seed discharge point with the pivot point located centrally) so that vertical movement of the opener was controlled as the average of the two linked wheels. Erbach et al. (1983) and Morrison et al. (1985), similarly, suggested that 'averaged' depth control was a viable proposition, with the walking beam-linked tandem wheels said to provide greatly improved depth control over a single wheel arrangement.

This walking beam/linked wheel principle has also been applied to the ground wheels that support the drill frame (Baker and Saxton, 1988) as well as to linking two depth control wheels located on either side of an opener unit (Anon., 1987; Campbell et al., 1985). A high degree of correlation ($r^2 = 98.5\%$) was exhibited between groove base height and soil surface height for a simple winged opener with the linked wheels set to sense depth immediately above the leading edge of the opener wing (Campbell et al.,

1985), although it was suggested that this arrangement for a non-rolling opener blade would, in practice, substantially reduce its residue handling capabilities.

The closer the depth control mechanism was placed to the actual opener, the more accurate the seed placement was likely to be (Morrison and Gerik, 1985a,b), providing penetration was adequate. In an assessment of both a trailed wheel and depth bands on the actual disc opener as alternative means of depth control, Morrison (1978) showed that depth bands, by providing depth regulation immediately beside the opener, allowed for more accurate seed depth sensing than a gauge wheel although, countering this, they were much more difficult to adjust. Erbach (1981) cited work by R.E.Baumheckel that apparently showed that not only were depth bands difficult to adjust, they also did not work well in wet soils. Morrison (1978) suggested that because of advantages and disadvantages inherent in both systems, an alternative mechanism for depth control that combined the good features of both was required. One option suggested was to locate the gauge wheels directly alongside the double disc openers (Morrison and Abrams, 1978).

Morrison and Gerik (1985a,b) studied the efficiency of four depth control designs (front wheels, rear wheels, linked front and rear wheels, and side wheels), in conjunction with a triple disc opener, both theoretically and empirically. Dual rear presswheels produced the most variable results with respect to accuracy of seeding depth. Dual front depth control wheels provided an improvement but were still significantly less effective than the other two options tested. Empirical testing showed that the side wheels provided similar performance to the linked wheel arrangement.

Because of the distance between rows, many row crop planters have had either one or two depth control wheels placed alongside each opener (Morrison et al., 1988). However, when considering depth control devices on no-tillage drills used for planting narrow-row crops such as cereals or pasture species, the situation has been complicated by the mechanical problems associated with the limited space that is available on drills that are producing row spacings as close as 150-200 mm. Because of this, depth control on these no-tillage drills has often been achieved by the use of some form of rear press wheel (Morrison et al., 1988). Morrison and Gerik (1983), for instance, suggested that dual rear press wheels were used for depth control on their drill design specifically because side wheels were said to make each opener unit too wide to be able to be configured for 200 mm row spacings.

Drills using this configuration for depth control, in conjunction with double disc openers, have been tested by the Prairie Agricultural Machinery Institute (PAMI, 1985; PAMI, 1986; PAMI, 1987) with varying results. In the case of the Lilliston 9680 (PAMI, 1985), seeding wheat at 6 km/hr, 68% of the seeds were placed within 6 mm of the average seeding depth although seed placement was said to be poor in heavy trash conditions. At the poorer end of the scale the Haybuster 107 (PAMI, 1986) and the Tye Series V 114-5360 (PAMI, 1987) placed 68% of the seeds within 16 mm and 17 mm of average seeding depth, respectively, although these tests were carried out at a speed of 8 km/hr. Increasing speed was said to increase seeding depth variability, probably due to increased seed bounce (PAMI, 1988). Another factor relating to speed of travel of double and triple disc openers was their tendency to suffer from "seed flick" at higher speeds (Baker and Saxton, 1988). This problem was caused by contact between the falling seed and the sides of the rotating discs resulting in displacement of the seed and, thus, greater variability in seeding depth.

One important factor to consider when studying the results of the aforementioned tests is that, in considering accuracy of seed placement, the Prairie Agricultural Machinery Institute appeared to have taken no account of ungerminated seeds either on or under the soil surface, suggesting that the true variability of the machines tested may have been greater than that actually stated in the test reports.

One way around this problem has been illustrated by the John Deere 750 Series All-Till drill (Anon, 1988) which uses a single semi-pneumatic gauge wheel, 113 x 400 mm (Deibert, 1990), located alongside a single, flat disc opener to provide depth control. Even with this configuration, the openers have been placed in two ranks spaced 1232 mm apart to achieve a 187.5 mm row spacing, thus allowing 375 mm lateral clearance between adjacent openers in each rank.

Another narrow row grain/pasture drill, as described by Baker and Saxton (1988), controlled depth via two angled wheels located on each side of the opener body and centred as close as was practical (approximately 250 mm rearward) to the seed discharge point. These openers were set in two ranks (1300 mm apart) with the openers further staggered (650 mm) on each rank by the use of spacing frames attached to every other set of parallelogram drag arms such that, even with a 150 mm row spacing, immediately adjacent openers were separated by 600 mm (Baker et al., 1979), a stagger which was largely dictated by trash handling considerations. Baker and Choudhary (1988) cited unpublished data from C.J.Baker which apparently suggested that this opener could be accurate within 10% of the target depth. Speed

did not appear to have much effect on seeding accuracy with this opener, with excellent results apparently being obtained at speeds up to 14 km/hr (Baker and Saxton, 1988). This same type of opener also produced more accurate placement of seed than a triple disc opener (with a rear press wheel for depth control) in trials carried out with soybeans in Australia (Baker and Desborough, 1985).

2.4 Summary

In agronomic terms, it seems clear that the depth at which seed is placed in the soil is an important factor in determining the evenness of emergence and overall success of establishment of the crop, as is the degree of variability around the target depth (i.e. the accuracy of seed placement). This target depth will vary from crop to crop and will also vary according to the prevailing climatic and, particularly, soil conditions. In this respect, no-tillage seedbeds have been shown to present a much greater problem than tilled seedbeds in terms of maintaining accurate depth control.

Despite ample evidence (often obtained from cultivated seedbeds) linking seeding depth variability with more uneven and also, most often, lower total emergence, the link through to effects on final yield is somewhat more tenuous. This appears to have been particularly so for grain crops harvested at full maturity (Benjamin, 1990), although the evidence to support a link has been more readily available where lower plant populations were considered.

However, the idea of improving accuracy of seeding depth, even if only to improve crop establishment alone, does appear to have merit irrespective of the argument surrounding yield effects. One example of this is the necessity to attain early and consistent establishment of winter wheat to prevent severe losses of plants over winter. The effect of this improved accuracy would be to reduce the unknown factors with regard to the number of plants which will actually establish from a given seeding rate. With the trend towards establishment of optimum populations for maximum yield it seems sensible to be as confident as possible regarding the percentage of seeds sown that actually emerge under a certain set of conditions, resulting in more efficient use of seed and, thus less expense in establishing the crop.

3. MATERIALS AND METHODS

3.1 Introduction

This experiment was designed to study the differences in performance of two crop species sown at a range of depths, with the aim of gaining an insight into possible design parameters regarding the accuracy required of depth regulating mechanisms on the Cross Slot™ opener used in this experiment. The Cross Slot™ opener (Fig. 3.1.1) was chosen as the basis of this experiment since past studies had suggested that it was superior to other types of no-tillage seed-drill opener in terms of biological reliability and tolerance over a wide range of conditions, promoting high levels of seed, seedling and overall crop performance (Baker, 1976; Baker et al., 1988).

The experiment involved three variables as follows;

- (1) two crop species
- (2) four seeding depths
- (3) two disc scraper options (with/without)

The performance assessments were based mainly around comparisons of various emergence parameters although a secondary aim was to analyse the response of one of the species (wheat) in terms of yield. The reason that lupin was not included in the yield study was due to potential problems with herbicides. The main form of weed control for lupins was simazine as a pre-emergent application. It was felt that any effect of this chemical on the emerging lupin seedlings might differ according to the depth at which they were planted (K. Harrington, pers. comm., 1992), resulting in a confounding effect on the results. Lupin is also very sensitive to the range of herbicides used for post-emergent control of weeds in wheat, which was planted alongside.

Any attempt to specifically relate changes in plant performance to specific changes in soil environmental factors with depth was felt to be beyond the scope of this trial and was not included in the objectives. However, some environmental measurements were made and are reported in the appendices for general consideration. A large number of samples would have been required to identify potential differences in soil bulk density between the small increments in depth under consideration in this trial (A. Palmer, pers. comm., 1992). Therefore, measurements of soil bulk density were not attempted. The fact that a soil penetrometer would give readings only in 50mm increments meant that measurement of soil strength would also have been of little real value.

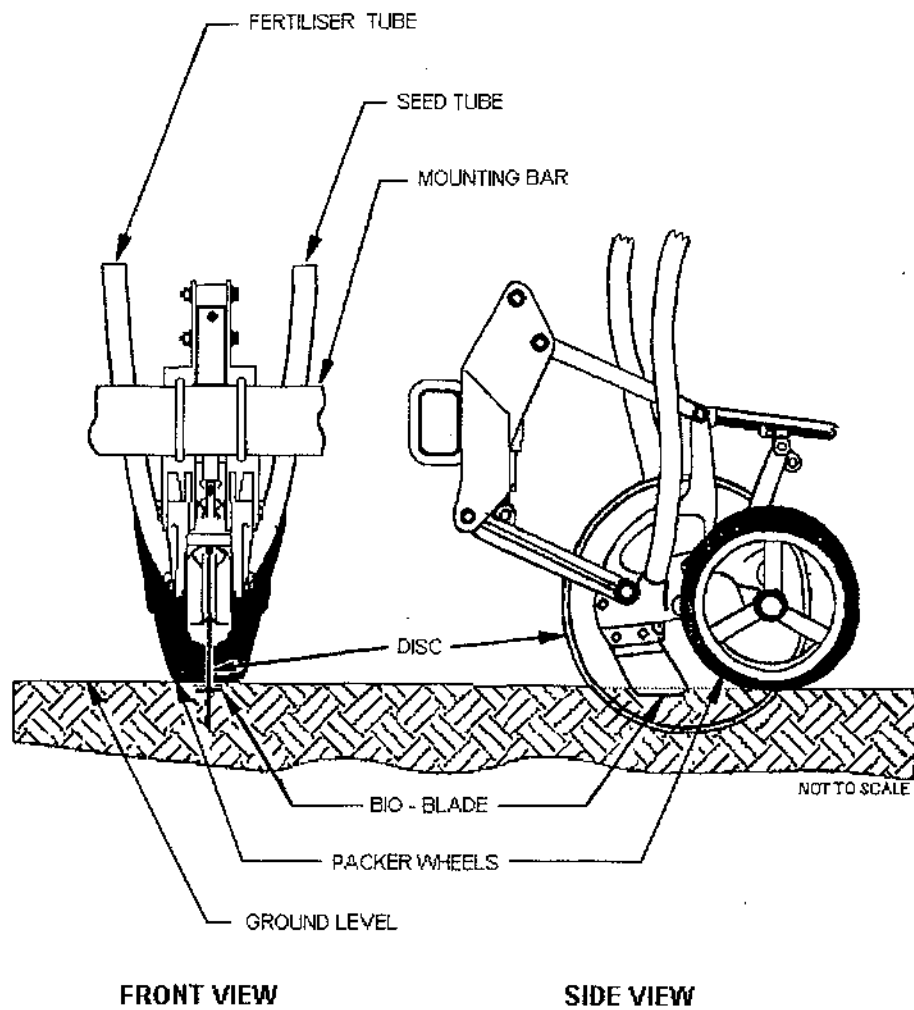


Figure 3.1.1. Diagrammatic representation of the Cross Slot™ opener.

3.2 Selection of experimental variables

The choice of variables was narrowed somewhat by the fact that only one opener type was to be used and that the study consisted of one major experiment on a single soil type. The options that remained were to plant different crops at a range of seeding depths. It was also considered useful to see if the addition of scrapers to the openers, designed to prevent the buildup of soil on the rotating central disc, had any effect on seed placement and/or seedling performance under the conditions of this experiment. In the case of scrapers there were only two options: (i) scrapers attached and (ii) scrapers removed.

The crop species selected were wheat (*Triticum aestivum* cv, Otane) and lupin (*Lupinus angustifolius*), the former being an example of a monocotyledon with hypogeal germination and the latter an example of a dicotyledon with epigeal germination. Numerous reports in the literature (e.g. White and Robson, 1989) indicated that dicotyledons with epigeal germination would be more sensitive to depth, but it was felt that it would also be useful to ascertain how a relatively depth-sensitive hypogeal monocotyledon might compare in terms of its reaction to seeding depth. To this end, Otane wheat was chosen because of its reported establishment response to relatively small changes in seeding depth in a cultivated soil (Johnstone et al., 1990).

The seeding depths were selected to cover the maximum depth that might be considered reasonable in a no-tillage system, given that the aim of sowing crops is to sow as shallow as possible while still maintaining the optimum environment for the seed and seedling (Perry, 1984). Thus the target depths chosen were:

- 20mm (D1)
- 30mm (D2)
- 50mm (D3)
- 70mm (D4).

Attempts were made to set the depth racks on the seed-drill openers to plant shallower than 20mm in a series of pilot runs. The uneven soil surface conditions of the trial area resulted in the lateral wings of the bioblades often breaking through the soil surface, leaving an unacceptable number of seeds on the soil surface.

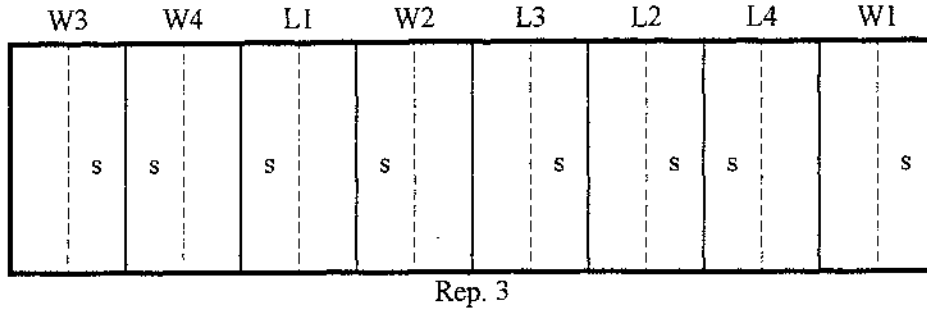
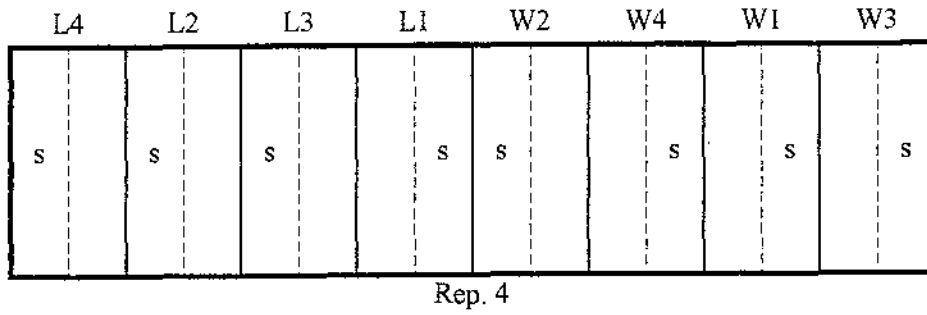
3.3 Experimental design

The experiment involved a total of sixteen treatments (2 x species, 4 x depths, and 2 x scrapers). The design consisted of a factorial main plot combination of depths and species, with a two-way split plot for the scraper treatments superimposed on each main plot. The scrapers were incorporated as a split plot because of practical considerations. This meant that the drill could be operated with half of the openers used having scrapers in place while the other half had the scrapers removed - obviating the need for time-consuming alterations to the scrapers during the course of planting the trial. The trial was laid out as a randomised complete block with four replications (Fig. 3.3.1). The allocation of both the main plots within each block as well as the positioning of the split plots within each main plot was randomised by drawing named slips of paper from a box containing all the possibilities for each block.

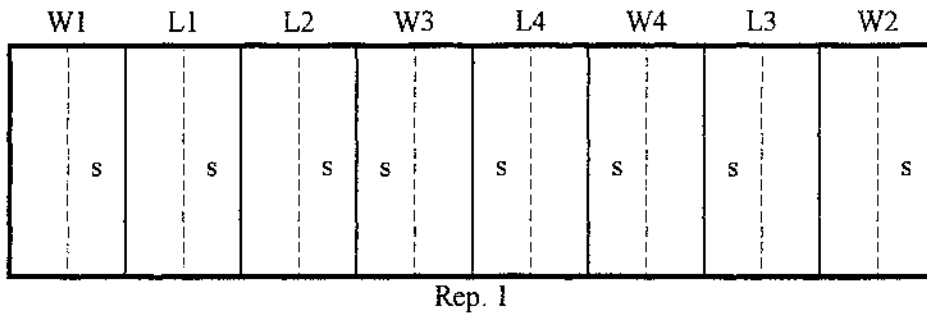
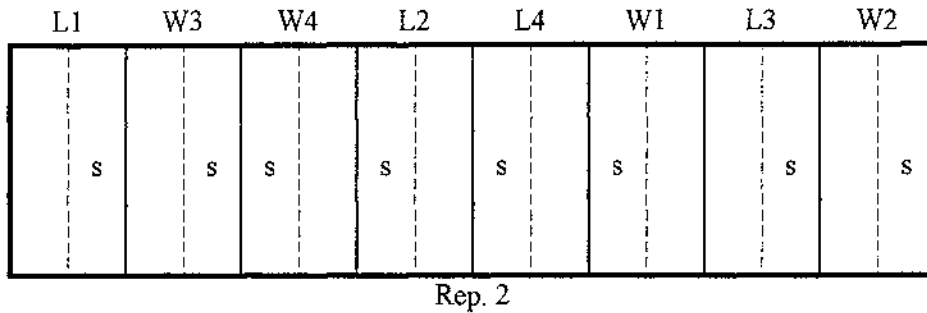
3.4 Site selection and preparation

The site selected for the trial was situated at the eastern end of the Frewens block, Massey University, adjacent to Old West Road. The soil at the trial site consists of a mixture of Manawatu and Rangitikei silt loams, with these two series having virtually identical characteristics in the top 200mm (approximately) of the soil profile. The paddock was in permanent pasture (grass/clover) and was near to completely flat. The site has a steep escarpment about 50 metres to the south with the Turitea Stream (flowing east to west) approximately 100 metres to the north. Because of this it was decided to account for any possible variation along the line between the stream and the escarpment by placing the blocks along that line (parallel to Old West Road).

The area required for the trial was sprayed on 7 November 1991 (see Fig. 3.4.1) with 3 l/ha Roundup® (360 g/litre glyphosate as active ingredient). The actual plots were marked out 14 days later, by which time the resident species had all died except for some evidence of survival of clover, which is not well controlled by glyphosate. Two days prior to planting, 30 kg/ha of ICI Slug & Snail Bait (18.0 g/kg metaldehyde as a granular bait) was applied to the trial area as a precautionary measure to eliminate any possibility of slugs eating seeds or seedlings.



← OLD WEST ROAD



N.B. * W = wheat, L = lupin

* 1 = D1 (20mm), 2 = D2 (30mm), 3 = D3 (50mm), 4 = D4 (70mm)

* 's' - denotes the sub-plots sown with scrapers attached

Figure 3.3.1. Layout of trial plots (not to scale) with main plots differentiated by solid lines and sub-plots differentiated by broken lines.



Figure 3.4.1. View of trial area looking south from Turitea Stream. Blocks were laid out with Block 1 closest and Block 4 furthest away from camera.

3.5 Field operations

3.5.1 Drilling

The seed drill used for this trial was the Massey University prototype no-tillage Cross Slot™ (or "Bioblade") drill towed by a John Deere 4250 tractor fitted with dual rear wheels (Fig. 3.5.1). The drill was fitted with sixteen openers at 150mm row spacing. To eliminate any possible compaction or scuffing effect from the tractor tyres, only the middle eight openers were used (four with scrapers and four without scrapers) since these eight openers operated in soil unaffected by the tractor tyres.

The trial was planted on 25 November 1991. Before commencement of drilling for each species, calibration of the drill was carried out so as to achieve, as closely as possible, the desired seeding rates of 300 seeds/m² for wheat (131 kg/ha) and 75 seeds/m² for lupin (144 kg/ha). Having decided on the appropriate setting for each species, a series of three calibration runs was carried out in each case, the averages of which were used as the actual seeding rates for each species. The values determined were 128 kg/ha for the wheat and 141 kg/ha for the lupin.

The wheat was drilled first starting with the shallowest depth (D1 - 20mm) and moving sequentially through to the deepest depth (D4 - 70mm). At the completion of drilling of wheat, remaining wheat seeds were vacuumed out of the drill and replaced with lupin seed. The lupin plots were then drilled in reverse order, from deepest through to the shallowest depth as a matter of convenience. Since the alterations in depth were achieved by repositioning a depth-adjusting rack on each opener, engineering logic suggested that no hysteresis would occur from changing the order of depth treatments between species. The state of the plots after seeding is illustrated in Fig. 3.5.2. The direction of drilling of each plot was determined by the orientation of the scraper sub-plots within each main plot. Since the positions of the openers with and without scrapers was fixed on the drill, the direction of drilling was the only way to effect the randomisation of the sub-plots.

The drilling was carried out at the relatively slow speed of around 2.5 km/hr. This was partly because of the desire to minimise any possible speed-related seeding depth variation and partly because of restrictions imposed by the space available on the lead-in to each plot. A "run-in" and "run-out" of at least 2 metres at each end of each plot was achieved to ensure that all the openers were at correct operating depth throughout the whole of the plot.



Figure 3.5.1. Massey University prototype "Bioblade" seed-drill used to plant the trial.



Figure 3.5.2. View of plot area after seeding, showing negligible soil disturbance.

3.5.2 Fertiliser

Wheat was the only crop under consideration for fertiliser, since only emergence parameters were to be measured for the lupin. It was decided not to place any fertiliser with the seed at drilling to remove any chance that seeds or seedlings might have been detrimentally affected. This precaution was taken despite the fact that this particular opener has been shown to be very effective in preventing such damage, even with minimal separation distances between seed and fertiliser (Baker and Afzal, 1986). Being under permanent pasture for several years with regular inputs of fertiliser meant that a relatively high existing level of fertility could be expected in the trial area.

Nitrogenous fertiliser was applied at the rate of 50 kg N/ha on 21 December 1991 when the average stage of growth of all the plants was about G.S.3 on the Feekes growth scale for cereals. The actual application was of 65 grams of urea (46% N) to each main plot (6 m²). This was equivalent to approximately 109 kg/ha of urea.

3.5.3 Weed control

As for fertilising, weed control was only of concern for the wheat plots. The aim was to eliminate competition from a range of broadleaf weeds that were growing amongst the wheat. The herbicide used was Salvo (each litre contains as active ingredients; 107 gms MCPA, 210 gms mecoprop, 233 gms dichlorprop and 17 gms dicamba) at a rate of 4 litres in 400 l/ha of water. This was applied using a knapsack and a four-nozzle hand-held boom which covered the complete width of each plot (1.2 metres) in a single pass. Extra 1.2 metre wide strips on both sides of each plot were also sprayed to maintain a clear area around each plot.

3.5.4 Anti-avian defences

Protection from birds of those parts of each wheat plot that were to be sampled for yield data was considered essential. To this end, a defensive strategy was put into place on 22 February 1992. This involved driving four wooden stakes into the ground, bounding an area 1.2 x 1.2 metres around the selected sampling area in each plot (see Fig. 4.8.2). Nylon bird netting was then draped over these stakes and secured at ground level with a number of metal pegs manufactured from 4mm

galvanised steel fencing wire. It was felt that this would defeat even the most determined of pedestrian avians, although later events showed that rats would not be kept out by this method.

3.6 Measurements

3.6.1 Depth and actual day of emergence

To determine the actual depth of planting for each treatment, 10 seeds/seedlings per drill row were dug up and their depth below the soil surface measured. This gave a total of 40 individual readings for each replication of each treatment. A random point on each row was allocated for this purpose and a length of row (determined by the theoretical seeding rate and the requirement for it to contain at least 10 seeds) was marked off on either side of that point. For wheat this length of row was 200mm (Fig. 3.6.1) and for lupin 600mm.

Within each length of row specified above, the plants (both wheat and lupin) that emerged on each day had a coloured wire tag attached (Fig. 3.6.1), with a different colour for each day of the trial. This meant that when each row was dug up to determine seeding depth, each seed/seedling had its day of emergence (if it emerged) recorded alongside it. Seeds that failed to produce emergent seedlings were, of course, also recorded and used in the calculation of mean seeding depth for each plot. Excavation to ascertain seeding depth for each plot commenced as soon as possible after it was evident that no more seedlings would emerge.

Because of the fact that there would be no actual seed to measure in the case of lupin (due to its epigeal germination pattern) investigations were carried out immediately after sowing the plots to determine where the lupin seed was ending up in the slot. This involved excavating a substantial number of segments of each drill row outside of the actual plot areas themselves. From this it was determined that the lupin seed was consistently being deposited on the base of the ledge formed by the horizontal wing of the opener, which was very easily defined under the existing soil conditions. An illustration of this is shown in Fig. 3.6.2. Thus, while the depth of wheat was measured from the seed itself (Fig. 3.6.3), the depth of lupin was measured using a



Figure 3.6.1. Illustration of sample row length for wheat, marked by orange paint. Also shows emerged seedlings tagged with different-coloured wire according to day of emergence.



Figure 3.6.2. Example of lupin seeds being consistently placed on the horizontal ledge in the seeding slot formed by the opener.



Figure 3.6.3. Measurement of seeding depth of wheat, with the seeds clearly visible.



Figure 3.6.4. Measurement of lupin seeding depth showing a clearly defined horizontal ledge in the seeding slot.

point 3mm (approximately half the diameter of the average seed) above the well-defined horizontal ledge as a reference point (Fig. 3.6.4).

3.6.2 Emergence counts

The numbers of plants emerging within a set area were recorded for both wheat and lupin. This involved the whole of each 5 metre long plot for lupin and, to achieve a similar total seedling count, a 1.2 m long section of each wheat plot (randomly selected). Counts were made on a daily basis from first emergence (day 7) through until day 22 and then every two or three days until final emergence (day 29). Counts on days 32 and 33 confirmed that emergence had ceased at this point. Seedlings counted as having emerged each day were identified by spraying with dazzle paint marker to ensure that they were not counted more than once (Fig.3.6.5).

In the case of wheat, seedlings were considered to have emerged when the tip of the emerging coleoptile passed through the plane of the soil surface. Lupin was considered to have emerged when the cotyledons were fully free of the seeding slot. In a situation where one or both cotyledons had broken off below the soil surface (e.g. Fig. 4.1.5) emergence was determined by the emergence of the first leaf.

3.6.3 Yield components

Yield components were measured for wheat only, not for lupin. Since scrapers showed virtually no effect on any of the emergence parameters, this factor was removed from the yield component results giving results on a main plot basis only (i.e. four replications of wheat at four depths). Sampling was done from the middle four rows of each eight-row main plot, thus including two rows sown with scrapers and two rows sown without scrapers in each sample area. The other two rows on each side served as guard rows.

Severe rat damage to the areas set aside for harvest (Fig. 4.8.2) dictated that yield results were determined by harvesting 30 ears of grain per plot, with one severely damaged plot failing to provide even this number. These figures were converted to yield by obtaining ear counts from areas of each plot outside the area set aside for yield. These areas had previously been stripped of seed by birds and were thus untouched by the rats. Ears were counted on plants from a 300mm length of each of



Figure 3.6.5. Illustration of the use of "dazzle" paint to mark the emerged seedlings as they were counted.

the four middle rows of each main plot (total 1.2 metres for each plot equivalent to 0.18 m²). These recordings were all carried out on 25 March 1992 (day 122).

The collected ears were left to air dry for four weeks and then hand threshed to obtain wet weights and seed numbers for each individual ear. The seeds from each plot were then bulked up and dried in an oven for 40 hours at ~70°C to obtain dry weights on a per plot basis.

3.6.4 Environmental measurements

3.6.4.1 Soil moisture

Sampling for soil moisture was carried out on four occasions through the emergence period, on days 2, 9, 17 and 26. A core sampler of approximately 20mm diameter was used to extract a soil core, the top 80mm of which was immediately cut up into four 20mm segments (Fig. 3.6.6) which were then placed in separate plastic bags and sealed to prevent moisture loss. This process was repeated four times within the area of each replication with the four samples from each depth range (0-20mm, 20-40mm, 40-60mm & 60-80mm) being bulked up in the same plastic bag for each replication. On each occasion the samples were immediately returned to the laboratory to obtain wet weights and then placed in an oven to dry for 48 hours at 70°C. The samples were then reweighed to obtain dry weights.

3.6.4.2 Soil temperature

Soil temperatures were monitored for several days around the time of first emergence of seedlings. Measurements were taken at the four nominal seeding depths (20mm, 30mm, 50mm & 70mm) at various times during the day over a four day period (days 7-10). "Zeal" 305mm laboratory thermometers (-10/+50°C) inserted into the soil to the appropriate depth were used for these measurements (Fig. 3.6.7). These figures were to be used to gain a general idea of the daytime temperatures being experienced at different depths, as well as comparing the degree of fluctuation at different depths. It was thought that this would provide some ability to extrapolate in general terms from more accurate, daily measurements of soil temperature data obtained from a nearby weather station operated by the New Zealand Pastoral Agriculture Research Institute Ltd (AgResearch).



Figure 3.6.6. Sampling method for soil moisture showing core sampler as well as the soil core cut into appropriate sample segments.



Figure 3.6.7. "Zeal" laboratory thermometer used for measuring soil temperature.

3.7 Limiting factors

The major limiting factor to consider in this study was the unexpected rat damage to the wheat plots prior to harvest. This meant much smaller samples to analyse and a consequential increase in the variability of the data. Fortunately, the yield aspect was of secondary importance in this trial and the problems did not in any way impinge on the main area of importance, namely the collection of emergence data.

The problem of assessing seeding depth of species with epigeal germination also needs to be considered in trials of this nature. Under the conditions of this experiment the problem was not great, but where there is no clear reference point from which to assess the position of the seed at some later date, alternative methods need to be found to measure the depth of the seed. Sampling to obtain plot means immediately after sowing would be acceptable, but would preclude any direct comparisons between depth and emergence on an individual seed basis.

3.8 Statistical analysis

Much of the statistical analysis was carried out by computer using the statistical analysis software package SAS® (Statistical Analysis Systems Institute, Carey, N.C., USA). Analysis of the experimental data was carried out under the assumption of a mixed model (Steel and Torrie, 1960), with species and scrapers fixed, and nominal depths being random. Output from the SAS® "ANOVA" procedure was used to produce synthetic error terms appropriate for the analysis of a mixed model split-plot design (Steel and Torrie, 1960). Calculation of F-tests and their significance, using the appropriate error terms for each source of variation, was carried out with the help of a computer program developed by Dr I.G. Gordon, Plant Science Department, Massey University. These analyses of variance, in conjunction with appropriate *t*-tests to determine significant differences between treatments, were carried out on the following parameters:

- (1) Actual depths achieved and variances around the mean depths
- (2) Total emergence
- (3) Rates of emergence (between 10% and 90% of those seedlings that emerged)
- (4) Days to 5% emergence

- (5) Days to 95% emergence
- (6) Yield, tiller numbers and seed weight (for wheat only)
- (7) Soil moisture data.

Simple linear least squares regression analysis of parameters (2) to (5) as a function of depth achieved was also carried out to determine the extent and form of any cause and effect relationships between seeding depth and the various emergence parameters. The same analysis was performed on the data relating seeding depths of individual seeds with their specific day of emergence.

Transformations of various data were carried out, as necessary, prior to an analysis being performed. Those transformations used are outlined below:

- A square-root transformation was applied to total emergence counts (Steel and Torrie, 1960).
- To compare variability of seed placement between treatments, the variance was chosen as the appropriate statistic to analyse, and was log-transformed prior to analysis (Steel and Torrie).

To determine the rates of emergence between 10% and 90% emergence (of those seeds that emerged) and to obtain an estimate of days to both 5% and 95% emergence, required that the asymmetric sigmoidal cumulative emergence curves be transformed to a straight line plot (I.G. Gordon, pers. comm., 1992). Comparison of both a logistic and a Gompertz transformation (Bliss, 1970) of the data (total count divided by cumulative count for each day) indicated that the log-log form of the Gompertz curve (Bliss, 1970) provided the better straight-line fit for the data. Small additions were made to both the total count and the cumulative count data (0.5 and 0.4, respectively) in the equation used for the transformation, so as to eliminate the possibility of trying to obtain the log of zero or a negative number (Steel and Torrie, 1960).

4. RESULTS AND DISCUSSION

Unless specifically noted to the contrary, all significant differences between treatments reported below are the result of t-tests carried out at the probability level of $P \leq 0.05$.

The target seeding depths were as follows:

20mm (D1)

30mm (D2)

50mm (D3)

70mm (D4).

4.1 Actual depths achieved

4.1.1 Results

The depth of seeds was determined by measuring from the soil surface directly above each seed to the bottom of the seed. This often equated to the depth of the ledge created by the horizontal wing of the opener blades since the opener was designed to place seeds on this ledge. The mean depths achieved for each species, as well as the overall means are presented in Table 4.1.1. The results indicate significant differences in depth, and interactions between species x depth. Results showing depth x scraper and species x depth x scraper interactions are presented in Table 4.1.2.

The results show that overall, the mean depths achieved were different for each nominal depth. This was also the case for wheat, but not for lupin where D1 and D2 were not significantly different. Even this last result, though, follows the trend with the actual depth at D2 for lupin being greater than for D1 at the lower order of probability of approximately $P \leq 0.11$. At nominal depths D1, D2 and D3 lupin was planted deeper than wheat. This was not the case at D4 where seeding depths for wheat and lupin were not significantly different.

The depth x scraper interaction (Table 4.1.2) showed that the addition of scrapers to the openers resulted in deeper planting only at D2 (31.1 for scrapers vs 27.6mm no scrapers). The second order interaction (Table 4.1.2) suggested that this only held true for wheat at D2 (29.7 vs 24.8mm), and not for lupin. Other results from the second order interaction showed that scrapers resulted in deeper planting of lupin than

Table 4.1.1. Actual seeding depths achieved for both species, at each nominal depth.

Nominal Depth	Overall (mm) [§]	Interactions	
		Wheat (mm) [‡]	Lupin (mm) [‡]
1 (20mm)	24.5 w	20.4 a	28.7 bc
D2 (30mm)	29.3 x	27.2 b	31.4 c
D3 (50mm)	48.1 y	45.2 d	51.0 e
D4 (70mm)	67.6 z	68.6 f	66.7 f

§ - Unlike letters in this column denote significant differences ($P \leq 0.05$).

‡ - Unlike letters in these two columns denote significant differences ($P \leq 0.05$).

Table 4.1.2. Actual seeding depths achieved showing interactions involving scrapers.

Nominal Depth	Scrapers	Overall (mm) [§]	Second order interactions	
			Wheat (mm) [‡]	Lupin (mm) [‡]
D1 (20mm)	with	23.5 v	17.8 a	29.2 cd
	without	25.6 vw	23.0 b	28.2 c
D2 (30mm)	with	31.1 x	29.7 cd	32.4 d
	without	27.6 w	24.8 b	30.5 cd
D3 (50mm)	with	48.9 y	45.2 e	52.7 g
	without	47.2 y	45.2 e	49.3 f
D4 (70mm)	with	67.9 z	68.3 h	67.5 h
	without	67.4 z	68.8 h	65.9 h

§ - Unlike letters in this column denote significant differences ($P \leq 0.05$).

‡ - Unlike letters in these two columns denote significant differences ($P \leq 0.05$).

Table 4.1.3. Natural logarithm-transformed variances of mean seeding depths achieved for both species, at each nominal depth.

Nominal Depth	Wheat [‡]	Lupin [‡]
D1 (20mm)	3.88	4.36
D2 (30mm)	4.08	4.20
D3 (50mm)	4.04	4.45
D4 (70mm)	4.09	4.40

‡ - No significant differences ($P \leq 0.05$) were found between any of the treatments.

no scrapers at D3 (52.7 vs 49.3mm) but that, contrary to this trend, scrapers resulted in shallower planting of wheat than no scrapers at D1 (17.8 vs 23.0mm).

An analysis of variance of the log-transformed variances of the mean seeding depths showed there were no significant differences between the scatter of actual depths achieved, even at $P \leq 0.10$. This indicates that the absolute variation of seed placement around the mean depth was similar for all combinations of species, depth and scrapers. Coefficients of variation (CV) ranged from 12.4% at D4 to 31.9% at D1.

4.1.2 Discussion

The uniformity of the variation in seeding depth (shown in Table 4.1.3) and the magnitude of the coefficients of variation suggest that the data had produced valid results. Overall, the target depths were achieved with a reasonable degree of accuracy and consistency, with the most notable discrepancy showing up with lupin at D1 where the actual depth of seeding was not significantly different from either wheat or lupin at D2.

It has been noted that the actual depth at which seeds end up in the soil is dependent not only upon the dynamics of the opener, but also on factors such as variations in both release position and the trajectory followed by the seed in free flight as well as displacement of seeds on impact with the soil (Bufton, 1984; Patterson, 1984; Ritchie, 1982). Another factor that can affect seed placement with this opener is contact between a rotating disc and the falling seed that might result in the seed being diverted from its vertical path by the disc. This is also a particular problem with double disc openers (Baker and Saxton, 1988). The rotating central disc of the Cross Slot™ opener could possibly have a similar effect if soil was allowed to build up on the disc, as might occur in some moist soil types with no scrapers attached to the openers (C.J.Baker, pers. comm., 1993).

The slow seeding speed of 2.5 km/h would appear to rule out speed as a major factor from either the aspect of increased seed bounce or seed flicking, especially since the Cross Slot™ opener used in this experiment has been claimed to perform accurately at speeds up to 14 km/h (Baker and Saxton, 1988). It is possible that the heavier, round lupin seed more readily dropped to the bottom of the horizontal portion of the slot than did the lighter, more irregularly shaped wheat seeds, which were often found

adhering to the soil several millimetres higher at the junction of the vertical slot and the top of the horizontal slot. Any buildup of soil on the disc would also appear to be less likely to affect lupin than wheat due to their respective seed shapes and weights. Whatever the reason for these differences in actual seeding depths between species, it did not result in any differences in variability around the mean seeding depth.

A partial explanation of the fact that actual depths at D4 were the same for both wheat and lupin may lie in the greater bulk and integrity of the soil mass (or "flap") above the lateral wing of the opener at this deeper depth. This is likely to have applied a more effective wiping action against the rotating disc than at shallower depths, preventing upward seed movement. The lesser bulk of drier, less cohesive soil being lifted by the wings at shallower depths may have resulted in a less positive suppressive action on upward movement of the seed.

Similar logic may be applied to the explanation for scrapers planting deeper than no scrapers at D2, although the reason for this occurring only at D2 is somewhat obscure. This may again be in part due to the effect of the greater soil mass acting as a more effective wiper against the discs at greater depths, effectively overriding the potential benefits of the scrapers, which were designed to achieve the same action. The second order interactions for both wheat at D2 and lupin at D3 followed the trend outlined above. This was not the case, however for wheat at D1, where scrapers resulted in shallower planting than no scrapers. Further investigation would be required to ascertain whether this effect was real or was simply a spurious result.

The fact that variation around the mean seeding depth was the same for all treatments illustrates that variability of this seed-drill opener is likely to remain fairly constant, in absolute terms, throughout a range of seeding depths.

4.2 Seedling emergence

All seedling emergence figures cited in this report refer to plant numbers established, since percentage emergence figures can only be calculated from a knowledge of exactly how many viable seeds were sown. An estimate from drill calibration was not considered sufficiently accurate to be used with confidence. However, it was considered that some idea of the approximate percentage emergence being obtained

would be useful. To this end, it was ascertained that, at the nominal seeding rates used, the nominal potential maximum plant populations were 71 plants per m² for wheat and 263 plants per m² for lupin. This adjustment was carried out on the basis of the results of germination tests carried out by the Seed Technology Centre, Massey University on the actual seed lines used in this experiment. The germination percentages for the lines of seed used were 90% for wheat and 97% for lupin.

4.2.1 Results

The seedling emergence figures (presented as plants/m²) for wheat and lupin at each nominal depth are presented in Table 4.2.1. Figures 4.2.1 and 4.2.2 show the regression plots for seedling emergence as a function of seeding depth for wheat and lupin, respectively. Table 4.2.2 shows the fate of seeds that failed to emerge, as determined by excavating to determine seeding depth.

Table 4.2.1. Final plant emergence counts (plants/m²) for both species, at each nominal depth.

Nominal Depth	Wheat§	Lupin§
D1 (20mm)	209 a (79.3‡)	65.9 a (92.8)
D2 (30mm)	210 a (79.9)	61.5 b (86.6)
D3 (50mm)	192 a (72.9)	42.6 c (60.0)
D4 (70mm)	160 b (60.8)	16.9 d (23.8)

§ - Unlike letters within each column denote significant differences ($P \leq 0.05$).

‡ - Numbers in brackets refer to nominal percent emergence calculated from seed-drill calibration.

Table 4.2.1 shows that the emergence of wheat was not significantly affected by depth within the first three nominal depths, although a reduction in emergence compared with the first three depths was noted at D4. Lupin reacted quite differently to depth compared with wheat. With lupin, increasing nominal depth of planting resulted in a corresponding reduction in emergence at each depth, although the largest reduction appeared to occur at D4.

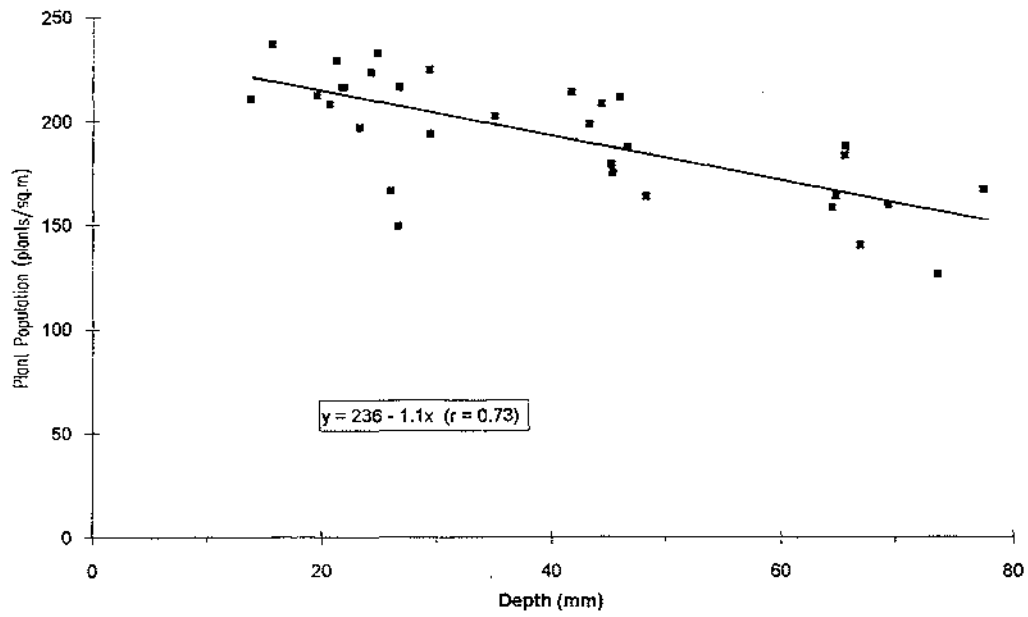


Figure 4.2.1. Regression plot of emergence as a function of depth for wheat. "r" is the correlation coefficient for the regression.

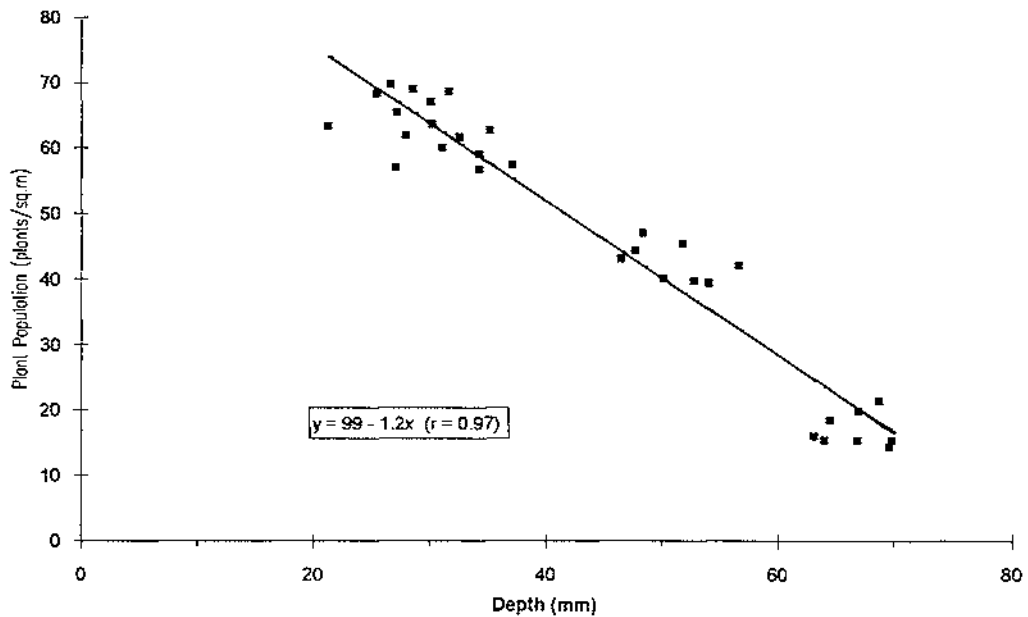


Figure 4.2.2. Regression plot of emergence as a function of depth for lupin. "r" is the correlation coefficient for the regression.

Linear regression analysis of seedling emergence as a function of depth for wheat (Fig. 4.2.1) showed a decrease in emergence of 11 plants/m² (equivalent to approximately 4.2%) for each 10mm increase in planting depth. The correlation for this regression was, however, only moderate ($r = 0.73$). The same analysis for lupin (Fig. 4.2.2) showed that this species was more sensitive to depth and also that it displayed a stronger linear response. The decrease in emergence for lupin was 12 plants/m² (equivalent to approximately 16.6%) for each 10mm increase in planting depth. These data should only be considered within the depth range studied in this experiment. Extrapolation, particularly to shallower depths could be misleading. The correlation for lupin was high ($r = 0.97$).

Table 4.2.2. Fate of those seeds that failed to emerge, as determined by digging up rows of tagged seedlings to determine depth of planting. Data pooled from both scraper treatments.

Nominal Depth	Wheat		Lupin	
	Failed to germinate	Germinated - <u>not</u> emerged	Failed to germinate	Germinated - <u>not</u> emerged
D1	17	12	0	4
D2	10	17	1	6
D3	10	28	7	75
D4	16	66	9	166

4.2.2 Discussion

As outlined in the literature review, general trends for percentage emergence have been for a decrease as the depth of planting increases, both in tilled and untilled soils. The results of this experiment suggest that, under the prevailing conditions, 'Otane' wheat responded to increasing seeding depth with a reduction in emergence, although the slope of the regression line suggests a relatively small response (equating to approximately 4% reduction in emergence for each 10mm increase in depth, within the depth range studied). It seems that a difference in seeding depth of around 20mm was required to produce a significant reduction in total emergence for wheat. This figure can only be a generalisation, however, because of the non-linearity of the transformed data used in the analysis of variance, and is noted only for the purposes of a general comparison with lupin. Also, the variation around the linear regression

line (Fig. 4.2.1) indicates a relatively high degree of variability in the response of wheat seedling emergence to depth. With respect to this, it should be noted that the difference in emergence for wheat between D2 and D3 only just failed to attain significance at the 5% level of probability and that it was significant at the lower order of probability of $P \leq 0.06$.

These results are in general agreement with those of Johnstone et al. (1990) who found that, for this same variety of wheat, deep planting (60-80mm) reduced emergence by 28% compared with shallow planting (30-40mm) in a cultivated soil. Many of the reports relating to wheat in cultivated soils show an even greater effect of depth (e.g. Whan, 1976) than has shown up in the results of this experiment, while others (e.g. Radford, 1986) have produced effects closer in magnitude to the above results. Morrison (1989) found that depths of 24, 54 and 83mm produced minimal effects on emergence of no-tillage wheat on a clay soil in Texas whereas both grain sorghum and cotton exhibited significant reductions in emergence with each increase in depth. Another trial using wheat in a cultivated soil (Kaufmann, 1968) also found no difference in emergence from depths of 25, 50 and 75mm.

Lupin, on the other hand, appeared to be more affected by seeding depth. This is not unusual since several authors have apparently noted the need to plant lupin at shallow depths to obtain satisfactory emergence, according to Lopez-Bellido and Fuentes (1986). All four nominal depths produced a consistent pattern of significantly decreasing emergence as depth increased. This trend was apparent between D1 and D2, even although the actual depths achieved for lupin at D1 and D2 may not have been significantly different (as discussed in section 4.1, the difference was significant only at the probability level $P \leq 0.11$). A similar response was found in the results of Campbell (1985) in a no-tillage trial in a similar soil type using a range of opener types. In his situation two different sowing speeds resulted in mean seeding depths of 32.4 and 35.3 mm, with corresponding respective percentage emergence figures of 85.3 and 80.3% for lupin. Although Campbell's increase in seeding depth was not significant, the resultant decrease in emergence was significant (both at $P \leq 0.05$). Wangdi et al. (1990) found that Russell lupin (*L. polyphyllus* x *L. arboreus*) had significantly higher establishment at 10 and 20mm seeding depth than at 30mm in a tilled soil.

The slope of the regression line for lupin (Fig. 4.2.2) highlights the much greater and more consistent sensitivity of lupin to changes in depth, compared with wheat. This greater sensitivity of lupin is not surprising given the trend of the reports cited in the

literature review. The high correlation also indicates a genuine linear emergence response to changes in seeding depth. This slope equates to an approximate decrease in percent emergence of 17% for every 10mm increase in seeding depth (within the depth range studied), which is approximately four times greater than the response of wheat. This, combined with the reduced scatter of data around the regression line, meant that changes in depth of as little as 3mm resulted in significant changes in seedling emergence. The same cautions regarding the non-linearity of transformed data that were expressed about the corresponding figure for wheat, also apply to this figure for lupin. The relative sensitivities of the two crops are important insofar as choosing the more sensitive crop would be the obvious option if one was compiling parameters to design a no-tillage drill capable of planting a wide range of crops.

Although temperature has been known to affect germination, given the evidence reported in the literature, it appears unlikely to have had an effect on total seedling emergence under the temperature conditions in this experiment (see Appendix 1).

Table 4.2.2 shows that, except for wheat at D1, in every case the majority of the reduced emergence with depth was accounted for by germinated but unemerged plants rather than by ungerminated seeds. This indicates that changing soil environmental conditions with depth had little effect on germination *per se* in this experiment. Despite the fact that visual assessment of plots at sowing showed few seeds on the soil surface, it is possible that some of the wheat seeds that were planted at the shallower depths and ended up on the soil surface may have been eaten by birds or mice, resulting in an underestimation of the number of ungerminated seeds at these shallower depths.

It was evident, both from observations made during seedling emergence and from excavation to measure the depth of seeding, that the seedlings in this experiment suffered from stresses imposed by soil strength and/or depth-related factors. This was especially so for the lupin seedlings, although wheat seedlings also showed evidence of having problems emerging from the greater depths, with leaves emerging from the coleoptile then becoming wedged and doubled over in the slot (Fig. 4.1.1) as well as tillers growing around "in circles" within the slot (Fig. 4.1.2) or becoming "concertinaed" when unable to penetrate a solid patch of soil (Fig. 4.1.2).

Lupin seedlings, particularly (but not solely) those emerging from D3 and D4, demonstrated problems such as bent (Fig. 4.1.3) or broken (Fig. 4.1.4) hypocotyls and loss of cotyledons (Fig. 4.1.5). Some seedlings also showed signs of disease or



Figure 4.1.1. Tip of emerging wheat leaf trapped below ground in seeding slot, resulting in breakage (nominal depth - D4).



Figure 4.1.2. Evidence of problems encountered by wheat tillers emerging from D4. Includes one tiller growing round in the horizontal portion of slot (a) as well as a tiller becoming "concertinaed" (b) by some obstruction on its way to the soil surface.



Figure 4.1.3. Example of a lupin seedling hypocotyl being severely bent because of the cotyledons being trapped in the seeding slot.



Figure 4.1.4. Example of a lupin seedling hypocotyl completely snapped due to cotyledons being unable to emerge from the seeding slot.



Figure 4.1.5. Example of late emerging lupin seedling (from D4 on day 24) having lost both cotyledons prior to emergence.



Figure 4.1.6. Example of lupin seedling that died within a few days of emergence, showing contorted and rotting hypocotyl below the soil surface.



Figure 4.1.7. Late emerging (day 16) lupin seedling showing severely rotted hypocotyl. Also shows the indirect path taken by some seedlings planted at shallower depths, increasing time to emergence.



Figure 4.1.8. Evidence of sub-surface hypocotyl damage being associated with the late emergence of lupin seedlings. The damaged seedling (red/orange tag - on far right) emerged 5 days later than the adjacent healthy seedling (white tag - second from right) from a similar depth.

rotting affecting the hypocotyl underground (Figs. 4.1.6, 4.1.7 & 4.1.8). This was more evident at D3 and D4 but also occurred at shallower depths where the hypocotyl sometimes took a less than direct path to the surface (Fig. 4.1.7, emerged day 16 from D1). The relationship between hypocotyl damage and speed of emergence is illustrated by Fig. 4.1.8 showing seedlings at D3. In this case two seedlings adjacent to each other and at similar depths emerged 5 days apart, the healthy seedling (white tag) emerged on day 11 while the seedling with the damaged hypocotyl (red/orange tag) did not emerge until day 16. Seedlings sometimes died within a few days of emergence. Fig. 4.1.6 shows an example of this in this experiment where the lupin seedling in question emerged with some difficulty on day 15 (brown tag just visible on soil surface), remained static for a few days and died soon after.

These results add to reports in the literature which indicate that problems for emerging epigeal dicotyledons subjected to depth and soil strength stresses can include the premature loss of one or both cotyledons and/or the breaking of, or formation of stress points on, the hypocotyl (Bowen, 1966; Rathore et al., 1981; White and Robson, 1989). Bowen (1966) also found that many cotton seedlings that emerged after being subjected to impedance stress died a few days after emergence. This was despite showing no apparent damage at emergence apart from some enlarging of the hypocotyl. The effects of broken or damaged hypocotyls is rather obvious but the effects of loss of cotyledons as the seedling emerges is perhaps less obvious. White and Robson (1989) cited a report by Caldwell which apparently stated that the loss of both cotyledons of soybean seedlings reduced yields by as much as 8-9%.

4.3 Rates of emergence

In discussing rates of emergence it was decided to consider the actual emergence of those seeds which did emerge. Thus the rates of emergence referred to in this section relate to an upper limit of 100%, being the total number of seedlings that emerged for a given treatment, rather than the total number of viable seeds planted. Further to this, it was considered appropriate to reduce the effect of the upper and lower 'tails' of the emergence curves, in order to reflect emergence rates of the majority of plants as represented by the straighter part of the emergence curve. From the curves generated for each plot an arbitrary range of emergence was selected between 10 and 90% of

those seeds that emerged. These rates of emergence are thus the inverse of the spread of emergence since they are derived from the division of a constant (80%) by the number of days between 10 and 90% emergence.

A log-log version of the Gompertz transformation (Bliss, 1970) was used on the emergence data to provide the best straight-line interpretation, given the shape of the emergence curves (I.G.Gordon, pers. comm., 1992). Analysis of the transformed data for each of the 64 plots showed all the correlation coefficients were greater than 0.95, with 57 of the plots greater than 0.98. This served to support the validity of using the transformation. The equations for the transformed data were used to obtain the points relating to 10% and 90% emergence which were then detransformed to give rates of emergence (%/day). To take account of the discarding of the upper and lower 10 percentiles, analysis of the days to both 5% and 95% emergence (as the mid-points of the discarded ranges) was included. These parameters also effectively served as measures of first and final emergence, respectively. Days-to-95%-emergence was considered to be the more important of these two parameters, however both are reported in a later section.

4.3.1 Results

The results are presented in Table 4.3.1, as well as Figs. 4.3.1 through 4.3.6. The latter are mean emergence rate curves presented by species and by depth. The slopes of lines drawn between the points A and B marked on each graph equate to the rates of emergence between 10 and 90% presented in Table 4.3.1 (expressed as % emerged per day of those seeds that actually emerged). The "y"-axes of the graphs, however, refer to the nominal percentage of viable seeds sown that actually emerged (derived from calculations outlined earlier in this report). This allows an overall view including not only the rate of emergence, but also total emergence. In the case of rates of emergence (Table 4.3.1), there were significant ($P \leq 0.01$) effects for both species and depths, but not for scraper effects or for any of the interactions.

It appears from Table 4.3.1 and Figs. 4.3.1 through 4.3.6 that lupin and wheat behaved remarkably similarly with respect to emergence rate changes with depth. The rates of emergence for both species did not differ between D1 and D2 or between D3 and D4 but rates were higher at the two shallower depths than at the two deeper depths. Initial regression analyses showed the slope of the regression line for wheat to be -0.09 ($r = 0.63$) and for lupin to be -0.13 ($r = 0.76$). These figures correspond to reductions in rate of emergence of 0.9 and 1.3 %/day, respectively, for each 10mm

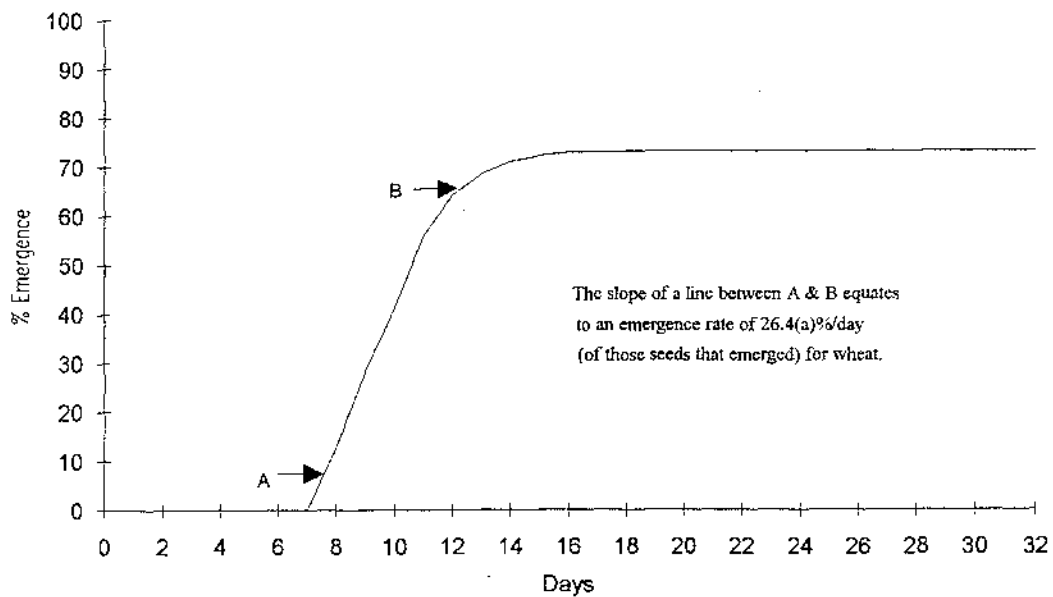


Figure 4.3.1. Emergence curve for wheat (data pooled from all depths) showing overall total emergence as well as rate of emergence of those seedlings that emerged. Daily rates of emergence figures (and unlike letters indicating significant differences) were obtained from Table 4.3.1.

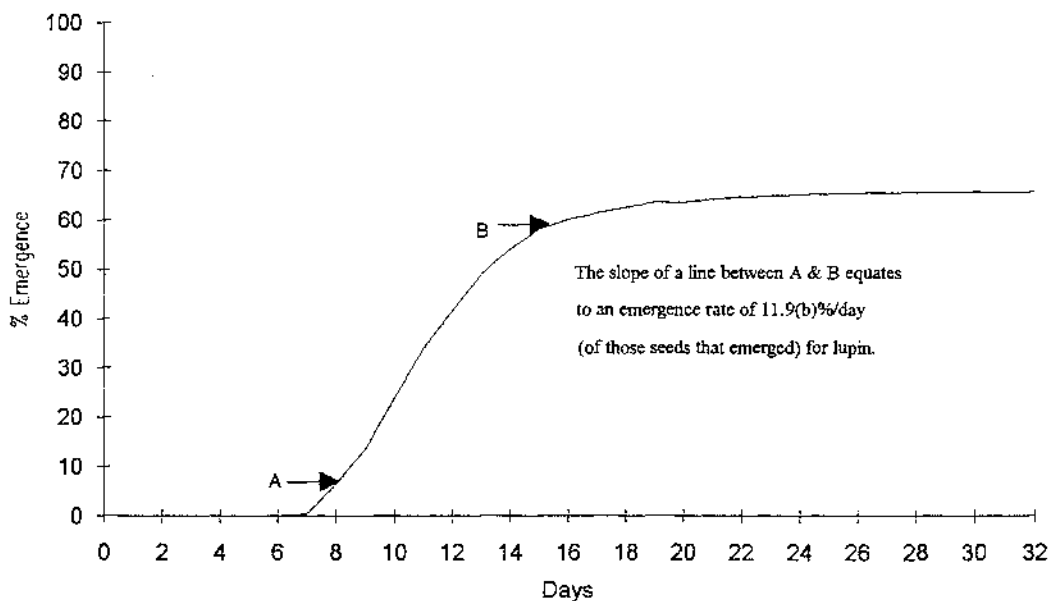


Figure 4.3.2. Emergence curve for lupin (data pooled from all depths) showing overall total emergence as well as rate of emergence of those seedlings that emerged. Daily rates of emergence figures (and unlike letters indicating significant differences) were obtained from Table 4.3.1.

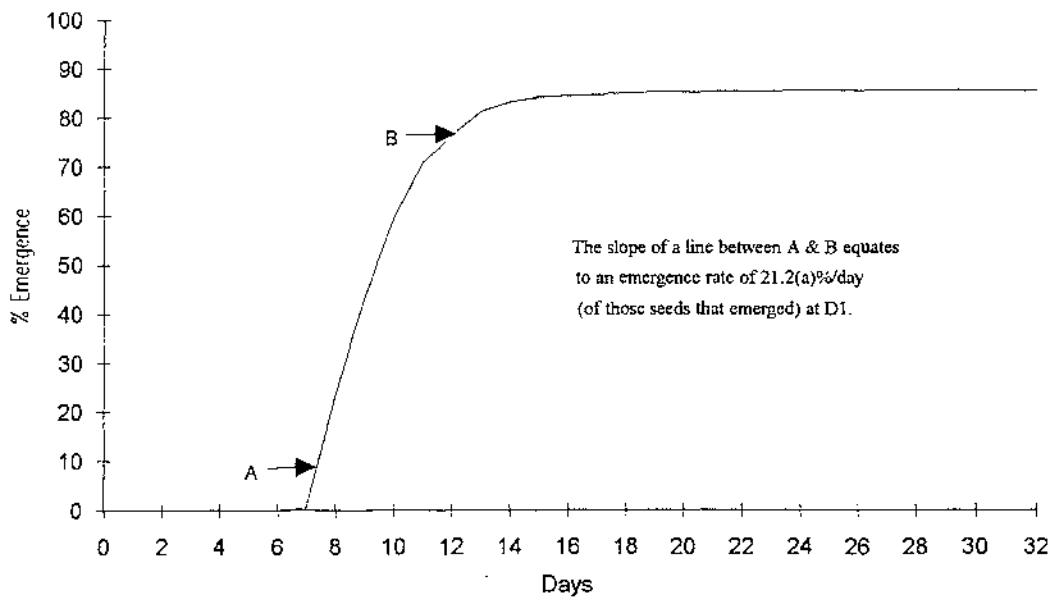


Figure 4.3.3. Emergence curve (data pooled from both species) for D1 showing overall total emergence as well as rate of emergence of those seedlings that emerged. Daily rates of emergence figures (and unlike letters indicating significant differences) were obtained from Table 4.3.1.

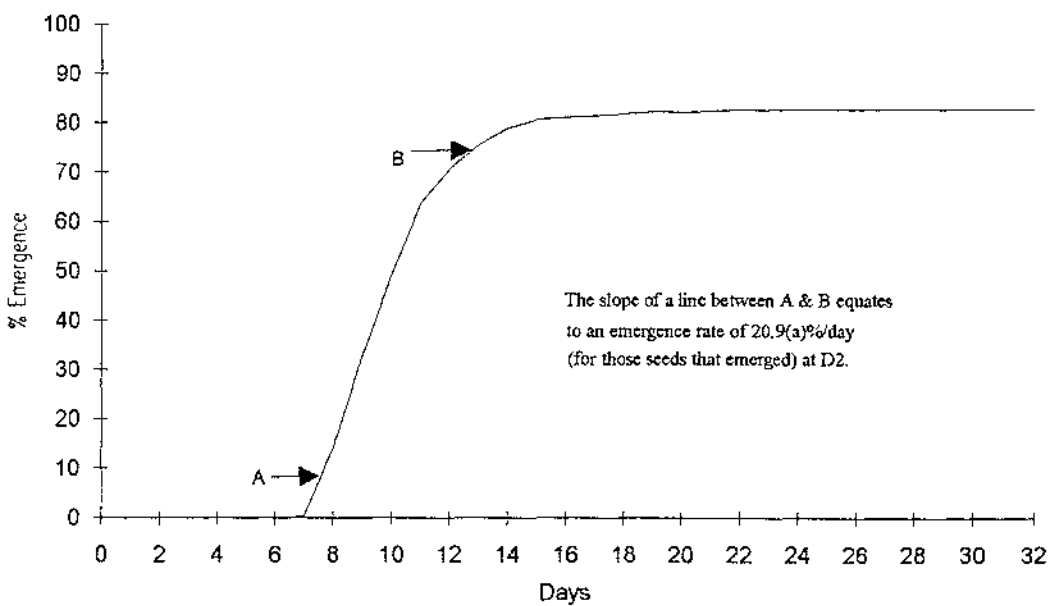


Figure 4.3.4. Emergence curve (data pooled from both species) for D2 showing overall total emergence as well as rate of emergence of those seedlings that emerged. Daily rates of emergence figures (and unlike letters indicating significant differences) were obtained from Table 4.3.1.

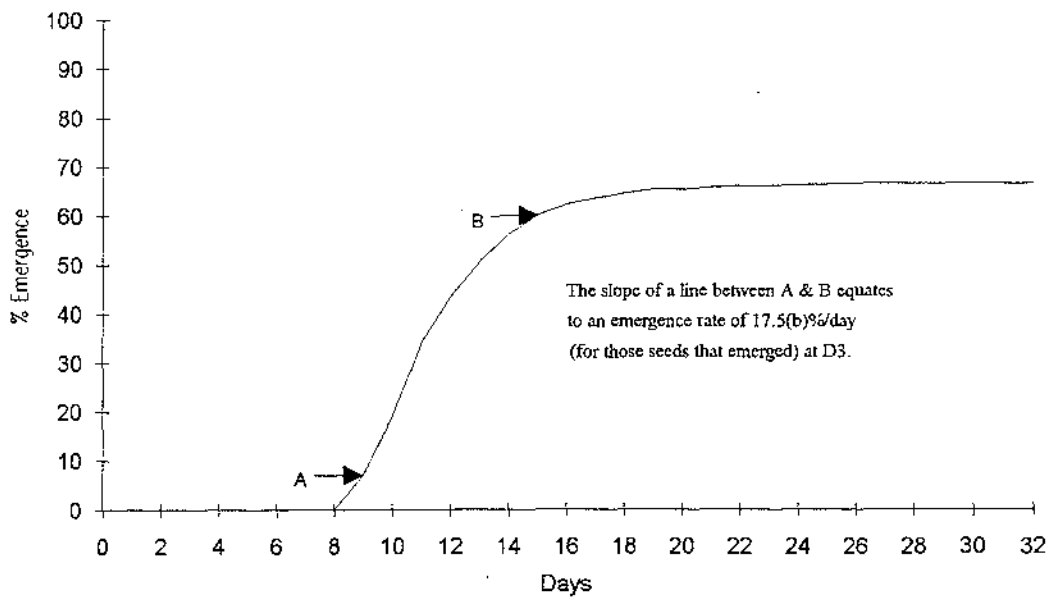


Figure 4.3.5. Emergence curve (data pooled from both species) for D3 showing overall total emergence as well as rate of emergence of those seedlings that emerged. Daily rates of emergence figures (and unlike letters indicating significant differences) were obtained from Table 4.3.1.

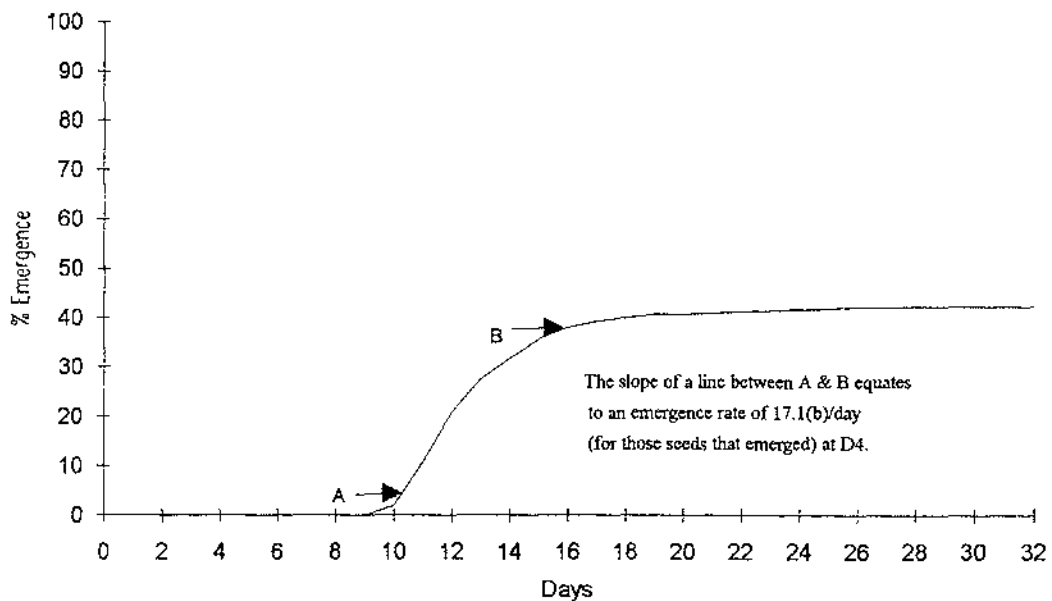


Figure 4.3.6. Emergence curve (data pooled from both species) for D4 showing overall total emergence as well as rate of emergence of those seedlings that emerged. Daily rates of emergence figures (and unlike letters indicating significant differences) were obtained from Table 4.3.1.

increase in seeding depth. Study of the regression plot for lupin, however, revealed one obvious outlying result (D1, no scrapers, block 3). Recalculation with this observation removed, as suggested by Moore and McCabe (1989) produced a slope of -0.11 with a correlation of 0.82. This brought the slope of the lupin regression line substantially closer to that for wheat, which is what would be expected given the results presented in Tables 4.3.1 and 4.3.2. Thus both species can be said to have suffered a reduction in rate of emergence of approximately 1%/day for each 10mm increase in seeding depth (within the range of depths studied), although the correlation data support this contention to a greater extent for lupin than for wheat. Despite this similar response, at a given depth wheat always emerged at about twice the rate of lupin.

Table 4.3.1. Daily rates of emergence (presented as percentage of plants emerging per day) of those seeds that emerged for both species at each nominal depth

Nominal Depth	Overall (%/day) [§]	Wheat (%/day) [‡]	Lupin (%/day) [‡]
D1 (20mm)	21.2 a	28.7 a	13.7 c
D2 (30mm)	20.9 a	28.2 a	13.7 c
D3 (50mm)	17.5 b	24.0 b	11.0 d
D4 (70mm)	17.1 b	24.8 b	9.3 d
	Species Means [□]	26.4 y	11.9 z

§ - Unlike letters in this column denote significant differences ($P \leq 0.01$).

‡ - Unlike letters in these columns denote significant differences ($P \leq 0.01$).

□ - Species means are significantly different ($P \leq 0.01$)

4.3.2 Discussion

This experiment shows clearly that the effects of depth upon the rates of emergence (of those seeds that emerged) were different from the effects upon total emergence. Although wheat showed an overall rate of emergence more than double that of lupin (Table 4.3.1), both species reacted similarly with respect to depth - as evidenced by the lack of depth x species interaction and the slopes of the regression lines. At nominal depths D1 and D2, emergence rates were not significantly different within species. The same held true for D3 and D4. However, the rates of emergence at D1 and D2 were significantly faster than those at D3 and D4 (Table 4.3.1).

This particular result suggests that the soil environmental factors affecting the speed with which those seedlings that survived actually emerged, are likely to have had a similar effect, with respect to depth, across both species. Although a greater range of species would need to be tested before generalisations could be made, the fact that two species as diverse in their emergence patterns as wheat (monocotyledon) and lupin (epigeal dicotyledon) could react similarly in terms of rates of emergence, suggests that other species may also react in a like fashion, at least under conditions similar to those of this experiment.

Countering this theory is that the correlation for the regression, for wheat particularly, was weak, raising the possibility of some form of curve better fitting the wheat data. It appears that wheat is naturally more variable than lupin in its response to seeding depth under no-tillage. It is also worth noting that further analysis of the interactive effects of species and depth showed that, for lupin, the difference in rates of emergence between D3 and D4 was significant at the lower order of probability of $P \leq 0.09$. This was not the case for wheat at these depths, or for either wheat or lupin between D1 and D2, where in all cases the differences were much less.

As stated in the results, over the depth range covered in this experiment, both wheat and lupin appeared to exhibit a similar, reasonably linear decline in rate of emergence with increases in actual depth achieved. Without more detailed information regarding the way in which soil environmental factors changed with depth under the conditions of this trial, it is not possible to more accurately determine the form of any cause and effect relationship between these factors and the rate of emergence. Also compounding the problem of describing any relationship is the fact that it is possible that those seeds that produce surviving plants from greater depths could be inherently more vigorous seeds, on average, than those producing surviving plants from shallower depths. This is based on the assumption that any effects which the more adverse conditions at the greater depth might have had on germination would be expected to produce selection pressure towards survival of inherently more vigorous seeds within each species (Lafond and Baker, 1986). This could help to offset the expected emergence rate-reducing effects of being sown at a greater depth, possibly resulting in a lesser response to changes in depth than might otherwise have been expected.

As with effects on percent emergence, soil strength probably had a large part to play in determining rates of emergence. Numerous authors have confirmed that soil compaction can affect the growth of both roots and shoots of pre-emergent seedlings

of a wide range of crops (Addae et al., 1991; Parker and Taylor, 1965; Perry, 1984; Klepper, 1987; Letey, 1985).

For rates of emergence, unlike percent emergence, temperature is more likely to have had some effect. Again, it is a well-documented fact that rate of emergence of a range of crops exhibits a positive correlation with temperature (e.g. Addae and Pearson, 1992; Addae et al., 1991; Alessi and Power, 1971; de Jong and Best, 1979). Although temperature data gathered using a mercury thermometer was considered by the author to be somewhat unreliable in absolute terms, especially at the shallower depths, it still indicated the normal trend of decreasing average temperature with increasing depth during the day and increased diurnal fluctuations near the soil surface. Temperature data gathered from an AgResearch weather station near the trial site is presented in Appendix 1. Studying daily air maximum temperatures and soil surface minimum temperatures and comparing them with soil temperatures at 100mm depth suggests that overall mean daily temperatures may not have varied much within the 0-100mm depth range during the period of germination and emergence. Any differences in temperature may, however, have resulted in some interaction between temperature and soil strength.

It is possible that moisture played a part in determining rates of emergence since a number of reports in the literature indicate this trend of decreased rate of emergence with increased soil moisture tension over a wide range of soil moisture levels (Gul and Allan, 1976; Lindstrom et al, 1976). However, soil moisture tension levels during emergence were never limiting, with a range of only 75-150 kPa at soil depths between 20 and 80 mm. The upper 20mm of the soil profile did reach soil moisture tensions of around 300-350 kPa (Appendix 1) in samples taken on day 2 (at planting) and day 26 (towards the end of the emergence phase). By day 4 (3-4 days before any plants emerged) rainfall had ensured that moisture levels in the top 20mm had increased well above the levels indicated by the sample taken on day 2. A positive water balance (Appendix 1) was maintained for virtually all of the emergence period with soil moisture tension (in the top 20mm) below 120 kPa for every day, except day 11, through until at least 80% of lupin had emerged from D4.

Overall it appears that, having isolated the effects of soil factors on total emergence (thus clearing the way for consideration of effects on rate of emergence of only those seedlings that emerged), the changes in soil environmental stresses with depth were not of sufficient magnitude to dramatically alter emergence rates. Although a change in depth of approximately 20mm was sufficient to produce a statistically significant

alteration to rate of emergence, this amounted to a change of only 2 %/day which, in practical terms, is not very large. With wheat emergence rates between 24 and 29 %/day in this experiment, a change of 2 %/day will make very little practical difference to the time taken for that 80% (between 10 and 90%) of the crop to emerge (e.g. 4 days at 25 %/day compared with 4.35 days at 23 %/day. The practical effect on lupin may be slightly greater because the emergence rate range was lower than that of wheat, at between 9 and 14 %/day (e.g. 8.33 days at 12 %/day compared with 10 days at 10 %/day).

4.4 Days-to-5%-emergence

Days-to-5%-emergence was considered to be an appropriate choice to represent the initiation of emergence. As well as being the mid-point of the lower 10% of emerging seedlings not considered in the rate of emergence analyses, it also served to eliminate the possible confusing effects of unusually late- or early-emerging seedlings in any plot, allowing for a more reasonable comparison.

4.4.1 Results

The results showing a depth effect as well as a species x depth interaction on days-to-5%-emergence are outlined in Table 4.4.1. A species x depth x scrapers interaction (Table 4.4.2) was also evident from the results of the analysis of variance. Figures 4.4.1 and 4.4.2 show the regression plots of days-to-5%-emergence as a function of seeding depth.

Overall, each increase in nominal depth resulted in an associated significant increase in days-to-5%-emergence ($P \leq 0.01$). The only exception to this within each species was for wheat, where the number of days-to-5%-emergence at D1 was not significantly different from D2. Within species, the differences were again significant at $P \leq 0.01$. Regression analyses (Figs. 4.4.1 & 4.4.2) indicated that each 10mm increase in seeding depth would delay the attainment of 5% emergence by 0.5 days for wheat ($r = 0.98$) and 1.1 days for lupin ($r = 0.95$). This second order interaction showed that for lupin at both D1 and D2 the addition of scrapers resulted in a reduction in the number

of days-to-5%-emergence (6.6 days for scrapers compared with 7.0 days for no scrapers at D1 and 7.4 days for scrapers compared with 7.7 days for no scrapers at D2).

Table 4.4.1. Days-to-5%-emergence overall and for both species, at each nominal depth.

Nominal Depth	Overall (days) [§]	Interactions	
		Wheat (days) [‡]	Lupin (days) [‡]
D1 (20mm)	7.0 w	7.1 ab	6.8 a
D2 (30mm)	7.4 x	7.4 bc	7.5 c
D3 (50mm)	8.8 y	8.5 d	9.2 e
D4 (70mm)	10.4 z	9.7 f	11.0 g

§ - Unlike letters in this column denote significant differences ($P \leq 0.05$).

‡ - Unlike letters in these two column denote significant differences ($P \leq 0.05$).

Table 4.4.2. Days-to-5%-emergence showing species x depth x scraper interactions.

Nominal Depth	Scrapers	Wheat (mm) [‡]	Lupin (mm) [‡]
D1 (20mm)	with	7.1 b	6.6 a
	without	7.1 b	7.0 b
D2 (30mm)	with	7.4 bc	7.4 b
	without	7.4 bc	7.7 c
D3 (50mm)	with	8.4 d	9.3 ef
	without	8.6 d	9.0 e
D4 (70mm)	with	9.7 fg	11.1 h
	without	9.8 g	10.9 h

‡ - Unlike letters in these two columns denote significant differences ($P \leq 0.05$).

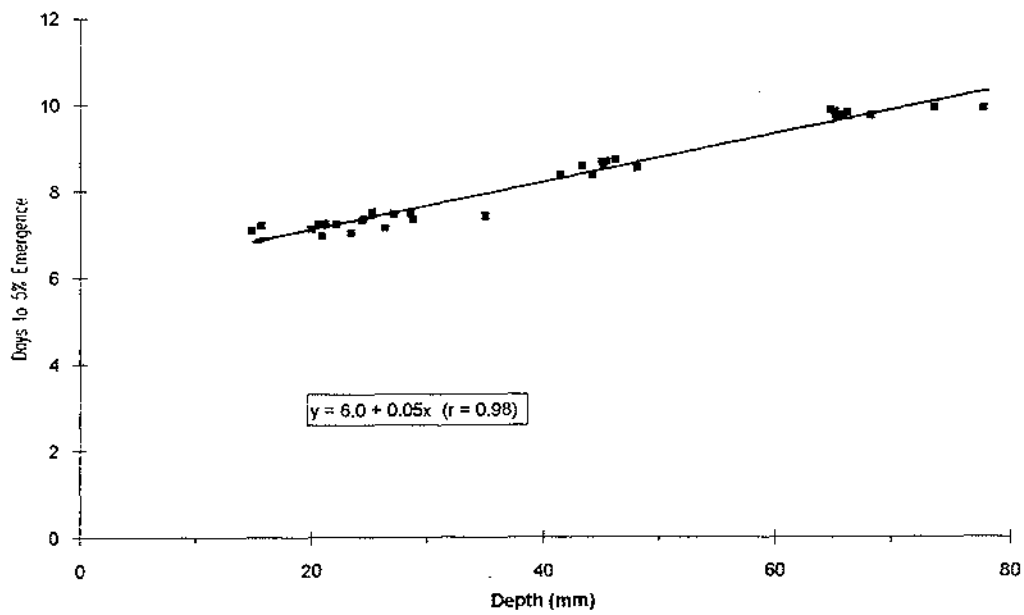


Figure 4.4.1. Regression plot of days-to-5%-emergence as a function of depth for wheat. "r" is the correlation coefficient for the regression.

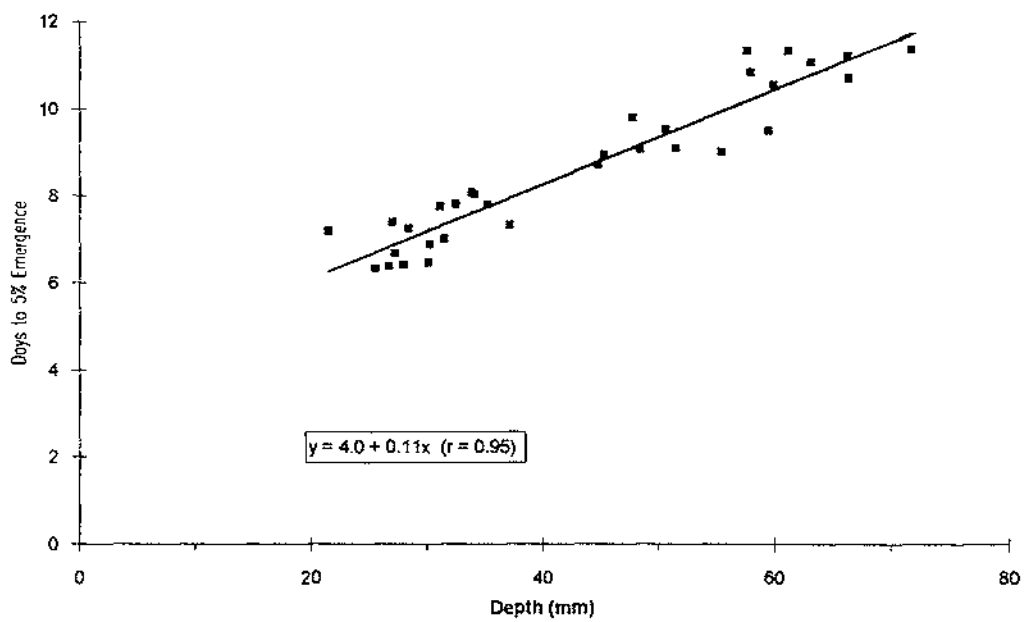


Figure 4.4.2. Regression plot of days-to-5%-emergence as a function of depth for lupin. "r" is the correlation coefficient for the regression.

4.4.2 Discussion

With respect to the second order interaction (species x depth x scraper), the results for days-to-5%-emergence (Table 4.4.2) appear somewhat confusing and certainly bear no relationship to the second order interaction for actual depth achieved. Study of the results of actual seeding depth for lupin show that for the corresponding four treatments (i.e. D1 with and without scrapers, D2 with and without scrapers) the only significant difference was between D1 without scrapers and D2 with scrapers. In terms of days-to-5%-emergence, however, the difference between these two treatments was, in fact, the only one that was not significantly different. If the results are valid, it certainly suggests only a tenuous link between differences in depth and days-to-5%-emergence at this level of interaction. Further work would need to be undertaken to gain an insight into the factors that might be influencing these results.

The fact that overall, the number of days-to-5%-emergence increased as depth increased (Table 4.4.1), is not surprising, even if only because of the greater distance that the emerging coleoptile or hypocotyl has to travel before arriving at the soil surface. Increased depth had been shown to have this effect on both wheat and lupin in cultivated soils (White and Robson, 1989). It could be expected that there was also an inherent spread of germination within each seed line. For wheat, which first emerged more quickly, and overall with a smaller spread, than lupin (Table 4.4.1), this may have been enough to mask any effect of depth on days-to-5%-emergence between D1 and D2, where the difference between actual seeding depths was less than 7mm. Orientation of the seed in the soil has also been shown to affect time to emergence with seeds planted 'upside-down' (shoot emerging downwards initially) taking longer than those planted 'right way up' (White and Robson, 1989).

As was the case with total emergence, the obvious sensitivity of lupin to depth resulted in a significant difference between D1 and D2 ($P \leq 0.01$) in terms of days-to-5%-emergence, when the actual depths achieved at D1 and D2 were significantly different only at the lower order of probability of $P \leq 0.11$. The slopes of the regression lines (Figs. 4.5.1 & 4.5.2) also reflect the greater effect of depth on lupin compared with wheat. The delay in attaining 5% emergence for any unit increase in seeding depth was more than twice as much for lupin than it was for wheat (1.1 days/10mm and 0.5 days/10mm, respectively). The high correlation coefficients for the regression (0.98 for wheat and 0.95 for lupin) should also be noted. The fact that these r-values are much higher than those reported in section 4.7 for the correlation between day of emergence and planting depth for individually tagged plants probably

relates to two main factors. The first is the smoothing effect that is likely to have occurred from using plot means for depth in the regression analysis. The second relates to the differing sensitivity between measurement of day-of-emergence of an individual plant and measuring the day on which 5% of the plot population had emerged. The latter measurement would have the effect of reducing the influence of genetic or seed orientation factors that could result in significant variations in day-of-emergence between two plants emerging from the same depth. The days-to-5%-emergence measurement would effectively treat those two plants the same if they both fell within the first 5% of the population to emerge.

In general, much of the discussion relating to edaphic factor effects on rates of emergence also apply to days-to-5%-emergence. Temperature effects on both speed of germination and rate of shoot elongation, combined with the increasing distance of travel from greater depths, would be expected to combine to produce slower initial emergence as seeds were planted deeper. The results of this experiment certainly support this contention.

4.5 Days-to-95%-emergence

As well as serving as a useful summary of the top 10% of the emergence curve, days-to-95%-emergence is also often used as a measure of effective full emergence to reduce the effect of any outlying results (I.G.Gordon, pers. comm., 1992). Days-to-95%-emergence is primarily a function of the previous two parameters discussed, i.e. if days-to-5%-emergence is combined with the rate of emergence between 10% and 90%, one can get some measure of when full (or 95% in this case) emergence is likely to occur.

4.5.1 Results

The significant results from the analysis of variance are presented in Table 4.5.1. Regression analyses of days-to-95%-emergence as a function of seeding depth were also performed for both species and are shown in Figures 4.5.1 and 4.5.2. Results from the analysis of variance showed both species and depth effects, as well as a

species x depth interaction. There were no scraper main effects, nor any interactions involving scrapers.

Table 4.5.1. Days-to-95%-emergence overall and for both species, at each nominal depth.

Nominal Depth	Overall (days) [§]	Interactions	
		Wheat (days) [‡]	Lupin (days) [‡]
D1 (20mm)	12.7 a	10.8 a	14.7 d
D2 (30mm)	13.2 b	11.1 a	15.3 e
D3 (50mm)	15.9 c	12.9 b	18.8 f
D4 (70mm)	18.2 d	14.0 c	22.3 g
	Species Means[□]	12.2 y	17.8 z

§ - Unlike letters in this column denote significant differences ($P \leq 0.05$).

‡ - Unlike letters in these columns denote significant differences ($P \leq 0.05$).

□ - Species means are significantly different ($P \leq 0.01$).

Both in terms of overall and within individual species results, days-to-95%-emergence followed closely the trend shown by those for days-to-5%-emergence. The overall result showed increasing days to emergence with each increase in nominal depth. Again, the lack of a significant difference between D1 and D2 for wheat was the only exception to this trend within species (Table 4.5.1).

As well as the above results, the two species were also different with wheat (12.2 days) attaining 95% emergence significantly faster ($P \leq 0.01$) than lupin (17.8 days). In fact, all of the wheat treatments had reached 95% emergence before the earliest of the lupin treatments (Table 4.5.1).

Regression analysis of days-to-95%-emergence as a function of depth for the plot means (Figs. 4.5.1 & 4.5.2) showed that a 10mm increase in seeding depth for wheat resulted in a delay of 0.7 days in reaching 95% emergence. The same increase in seeding depth for lupin produced a corresponding delay of 2.0 days in time taken to reach 95% emergence. The correlation coefficients for the regressions were the same for both species at $r = 0.95$.

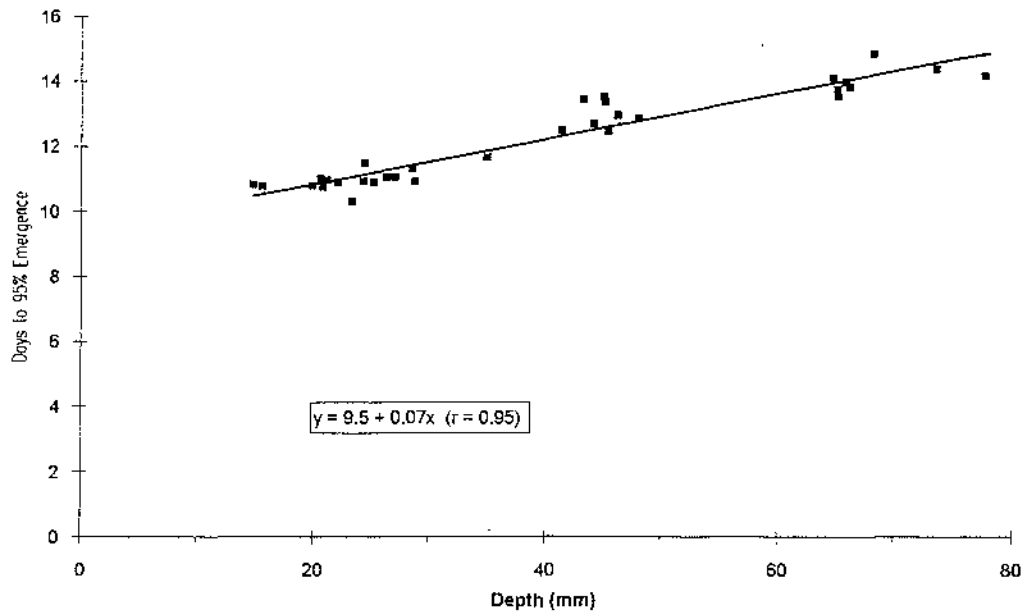


Figure 4.5.1. Regression plot of days-to-95%-emergence as a function of depth for wheat. "r" is the correlation coefficient for the regression.

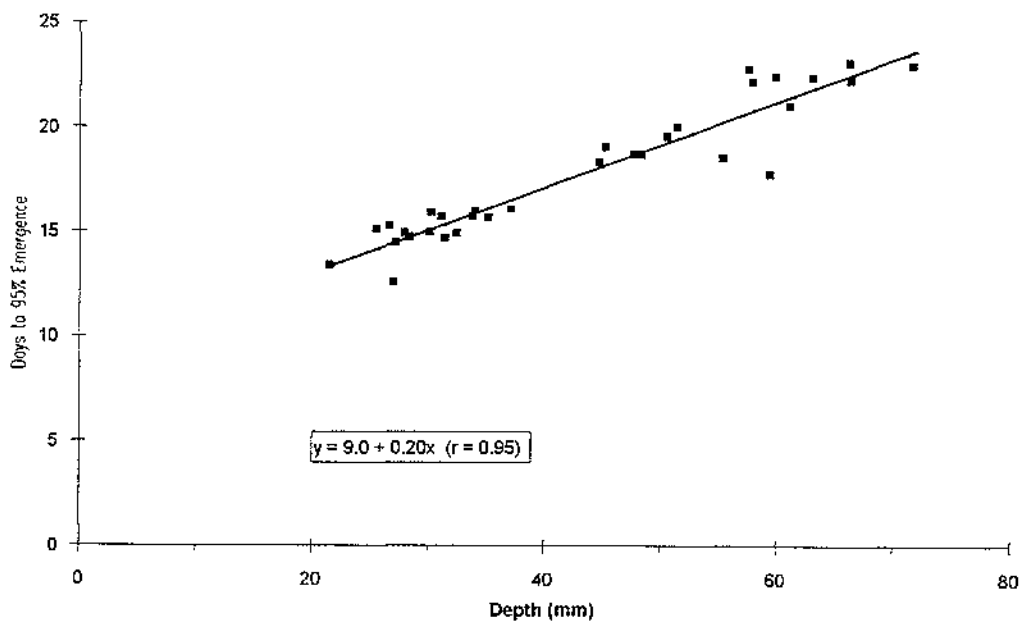


Figure 4.5.2. Regression plot of days-to-95%-emergence as a function of depth for lupin. "r" is the correlation coefficient for the regression.

4.5.2 Discussion

Remembering that the rates of emergence for both wheat and lupin were not different between D1 and D2 or between D3 and D4 (Table 4.3.1), one would expect the respective significant differences (or lack thereof) between nominal depths, for both wheat and lupin, to be very similar for days-to-5%-emergence as for days-to-95%-emergence. Tables 4.4.1 and 4.5.1 bear this relationship out, as does the high level of correlation between days-to-5% and 95%-emergence for both wheat and lupin (Table 4.6.1).

Wheat was again less affected by depth than was lupin. The difference between days-to-95%-emergence at D1 and D4 was only 3.2 days for wheat whereas the spread for lupin was 7.6 days. The slopes of the regression lines indicate that each 10mm increase in seeding depth delayed the attainment of 95% emergence by 0.7 days for wheat and 2.0 days for lupin. This indicates that where attaining quick, relatively even emergence of those seeds that emerge is a priority, seeding depth will be less of a concern for wheat than it will be for lupin, or for any other species that showed similar sensitivity. The practical significance of delays of this magnitude is likely to vary depending on the crop and on the specific reasons behind the requirement for even emergence (i.e. whether they relate to general yield considerations or to factors such as attaining the required stage of development of winter wheat before the onset of the winter freeze, for example).

These results could again be expected to be dependent on soil environmental conditions, with more adverse conditions probably causing the differences between depths to be more exaggerated. Soil temperature and soil strength, as outlined earlier, would again be likely to play a major role in determining the time to full emergence of a crop through their effects on both speed of germination as well as emergence rates.

4.6 Relationship between emergence parameters

4.6.1 Results

The respective correlation coefficients between the various emergence parameters are presented in Table 4.6.1. The results show that the correlation between parameters in the case of lupin tended to be similar to or stronger than the corresponding correlations for wheat. The three comparisons in which the correlation coefficient (r) for lupin was noticeably greater than for wheat, were where emergence was also closely correlated with each of the other three parameters. All other r -values were similar for wheat and lupin.

There was a strong correlation between days-to-5% and days-to-95%-emergence for both wheat and lupin ($r = 0.97$ and 0.94 , respectively). In the case of lupin there was also a strong correlation between total emergence and days-to-5%-emergence ($r = -0.97$) as well as between total emergence and days-to-95%-emergence ($r = -0.95$) while the corresponding correlations for wheat ($r = -0.70$ and -0.69) were only moderate. There were only weak to moderate r -values comparing rate of emergence correlated with both total emergence and days-to-5%-emergence for both wheat (0.46 and -0.62 , respectively) and lupin (0.70 and -0.67 , respectively). There was, however, a reasonably strong correlation between rate of emergence and days-to-95%-emergence for both wheat ($r = -0.80$) and lupin ($r = -0.87$).

Table 4.6.1. Correlation coefficients for all combinations of rate of emergence, emergence, days-to-5%-emergence and days-to-95%-emergence for both wheat and lupin.

Correlation	Rate of emergence (10-90%)		Total emergence		Days-to-5%-emergence	
	Wheat	Lupin	Wheat	Lupin	Wheat	Lupin
Total emergence	0.46	0.70	-	-	-	-
Days-to-5%-emergence	-0.62	-0.67	-0.70	-0.97	-	-
Days-to-95%-emergence	-0.80	-0.87	-0.69	-0.95	0.97	0.94

4.6.3 Discussion

Although the relativity of these various correlation coefficients can be deduced from the correlation coefficients for the regressions of these emergence parameters as a function of depth, it is useful to see the actual correlations as a summary of how the various emergence parameters related to each other. Probably the most important point is that no single parameter on its own, of those measured in this experiment, could be used to give a truly accurate summary of how depth might affect the performance of the emerging seedlings overall. It can also be readily seen that the two species under study have reacted differently.

One good example of this is the correlation of lupin total emergence with days-to-5%-emergence ($r = -0.97$), days-to-95%-emergence ($r = -0.95$) and rate of emergence ($r = 0.70$). For this species, soil environmental stresses that might be expected to affect total emergence might also be expected to exhibit quite similar trends in their effect on both days-to-5% and days-to-95% emergence and, to a lesser extent, on rate of emergence. The respective correlations for wheat were 0.70, 0.69 and 0.46, indicating a weaker link between total emergence and the other measured parameters for this species. This occurrence can be explained by the regression correlations between emergence and depth for the two species (wheat, 0.73 and lupin, 0.97) showing far less consistency in emergence data for wheat than for lupin. From this, one could suggest that soil environmental conditions that resulted in reduced total emergence of lupin would have a similar effect in terms of delaying both initial and final emergence, with the link between emergence and rate of emergence being far more tenuous. The same could not be said for wheat, however, where soil environmental effects on total emergence bear very little relationship to their effects on the other emergence parameters, especially on rate of emergence.

It is therefore important to study all of the appropriate emergence parameters when undertaking trials of this nature rather than automatically using one or two as a summary indicator of how a species will perform under a given set of conditions. For example, if rate of emergence of the plants that actually emerged was considered to be the most important factor in wheat plant performance in a particular situation, then it would be inappropriate to use a measurement such as percent emergence as an indication of relative plant performance. The results also show that different species are almost certainly going to be different in this respect, with the use of one or two parameters alone as an indicator of overall response to depth effects being more valid for some species than for others under a given set of conditions.

4.7 Relationship between depth and day of emergence

4.7.1 Results

Table 4.7.1 presents the correlations between actual depth and actual day-of-emergence for both wheat and lupin.

Table 4.7.1. Correlation between depth and day of emergence for both wheat and lupin. Data derived from a number of individually recorded seedlings.

	Wheat	Lupin
Correlation coefficient	0.74	0.74

These results for actual day-of-emergence were obtained from the portion of the experiment where a number of individual plants in each plot were colour-coded according to the day on which they emerged and later dug up to ascertain their respective seeding depths. These results thus take no account of those seeds which were found to have either failed to germinate or to have germinated but failed to emerge.

The correlation coefficient for the relationship between day-of-emergence and seeding depth was carried out on data pooled from all treatments for each species, resulting in more than 900 individual data points for both wheat and lupin. The strength of the correlation was similar for both species ($r = 0.74$).

4.7.2 Discussion

The results indicate that, for both wheat and lupin, the variation in actual depth at which the seed was planted directly accounted for approximately half of the variation in day of emergence ($r^2 = 0.55$), with the other half of the variation coming about as a response to other factors. This result shows that factors other than the distance that the emerging seedling has to travel to reach the soil surface play an important role in determining the actual day of emergence. It is worth reiterating that one factor that may affect this correlation, particularly causing greater variation at shallower depths, is the orientation of the seed (White and Robson, 1989). This could result in two

seeds being measured as having identical depths but differing in actual emergence distance by an amount at least equal to the diameter of the seed. Even if these seeds germinated on the same day they may well emerge some time apart.

Another factor that is likely to be involved, as mentioned previously, is the inherent genetic variation that might be expected within a given seed line. This would result in a spread of time over which the germination process occurs, even when all seeds were subjected to identical environmental conditions (such as a laboratory germination test). The extent to which this factor contributed to the unexplained portion of the depth vs. day of emergence relationship, would require further research to determine. This would probably entail carrying out a series of germination tests with the seeds subjected to varying levels of stress. From this it would be possible to obtain an idea of the natural variation or spread of emergence within any seed line of a particular species.

It has also been shown that the timing of emergence of individual seedlings, particularly dicotyledons with epigeal germination, can be affected by a phenomenon known as 'mass action' (Arndt, 1965; Parker and Taylor, 1965). This occurs where the combined forces of several seedlings sown very close together result in upheaval of the soil as they emerge (Fig. 4.7.1). The result is that the day of emergence of the seedlings involved will be in advance of that which would have been expected of each individual seedling emerging singly, without the influence of the others. This factor is likely to have increased the variability of the lupin data in particular.

As mentioned previously (Section 4.4), the fact that these unpredictable factors appear to have contributed to the poor correlation is partly supported by the higher correlation between depth and days-to-5%-emergence at the plot level. Taking the days-to-5%-emergence on a plot basis reduces the effect of the variability of the early emerging seeds.

Without this information regarding such factors as genetic variability and orientation, it is not possible to determine how much of the unexplained variability in day of emergence vs depth relationship might be attributable to any other contributory factors. It seems likely that, having obtained an estimate of genetic variability, much of the remaining variability could be attributed to other stresses applied to the seed and emerging seedling by the soil environmental conditions that prevailed at the particular depth at which the seed was planted. Ascertaining the extent to which



Figure 4.7.1. Illustration of the phenomenon of 'mass action', resulting in the more rapid emergence of some lupin seedlings.

individual factors such as soil strength, moisture, temperature and aeration contribute to the stresses applied to the emerging seedling would require a detailed analysis of the changes in soil environmental conditions with depth along with emergence data similar to those obtained in this experiment.

4.8 Yield, tiller numbers and seed weight for wheat

Due to variable damage by rats to the areas set aside for yield sampling (see Figs. 4.8.1 and 4.8.2), yield and seed weight results were unable to be obtained from one plot due to insufficient undamaged ears of wheat being available for harvest. The plot in question was the first replication of the D1 treatment. Tiller counts were unaffected since they were obtained from parts of the plots from which birds had already stripped the seed, resulting in no rat damage to those plants. The subsequent missing plot analysis meant that means for D1 had a higher standard error than means for the other nominal depths.

Because of this rat damage, which possibly affected the randomness of sampling due to reduced choice of plants in each plot, the author feels that the yield and seed weight results should be treated with caution. The tiller numbers, however, are more reliable for the reasons outlined above.

It should be noted that all yield and thousand-seed-weight (TSW) results are presented on a dry weight basis, which should be taken into account if comparisons are to be made with other trials where yield of wheat may have been adjusted to a base moisture content of 14%.

4.8.1 Results

Table 4.8.1 shows the results for yield and thousand-seed-weight of the harvested seed, as well as the fertile tillers populations, for wheat at each of the four nominal depths.

To circumvent anomalies arising from the fact that the mean seed weight for D1 had a higher standard error than those at other nominal depths, these particular results (seed weight only) are shown as tested for significance at the order of probability $P \leq 0.06$. Yield and tiller numbers are shown at $P \leq 0.05$. The results are presented in Table 4.8.1 as yield (kg/ha), TSW (thousand seed weight - grams) and tiller numbers per square metre. The tiller numbers referred to were counted at crop maturity and thus represent the number of fertile tillers that produced an ear of grain.

Tiller numbers showed significant differences between all four nominal depths with D2 having the highest count of 426 tillers/m², followed by D1, D3 and D4 in descending order. The figures for yield at the different depths mirrored these in terms of ranking. Despite this trend, yields at D1, D2 and D3 were not significantly different at $P \leq 0.05$, although all were significantly greater than the yield at D4. However, the difference between D2 (5580 kg/ha) and D3 (4697 kg/ha) was seen to be significant at the lower order of probability of $P \leq 0.09$. There were relatively small differences between nominal depths in terms of thousand-seed-weight with D1, D2 and D3 all being similar and D3 and D4 also similar. Both D1 and D2 had a higher thousand-seed-weight than D4.



Figure 4.8.1. Evidence of the fact that rats were responsible for damage to wheat plots.



Figure 4.8.2. Example of severe rat damage to wheat plot (between four pegs used to support bird netting). Comparison can be made with the standing tillers in the foreground where no rat damage occurred because of the prior stripping of seed by birds.

Table 4.8.1. Yield and thousand-seed-weight (TSW) of harvested seed, and fertile tiller populations for wheat at four different depths.

Depth	Yield (kg/ha) [‡]	TSW (g) [§]	Tillers/m ² [‡]
D1 (20mm)	5232 a	40.1 a	403 b
D2 (30mm)	5580 a	40.0 a	426 a
D3 (50mm)	4697 a	36.8 ab	371 c
D4 (70mm)	3282 b	32.8 b	275 d

§ - Numbers in this column followed by the same letter are not significantly different at $P \leq 0.06$.

‡ - Numbers in these columns followed by the same letter are not significantly different at $P \leq 0.05$.

4.8.2 Discussion

The most notable results from these data are probably the order in which the nominal depths ranked in terms of tiller population ($D2 > D1 > D3 > D4$). None of the emergence parameters measured showed any significant difference between D1 and D2 for wheat at any stage, yet the final tiller population was greater at D2 than at D1 ($P \leq 0.025$). This confirmed observations at the time of the experiment that appeared to suggest that the wheat plots at D2 were performing slightly better than those at D1, with plants appearing a little more vigorous. The trend was the same for yield although the 7% difference between D1 and D2 was not significant. The difference in yield between D2 (5580 kg/ha) and D3 (4967 kg/ha), which is shown as non-significant ($P \leq 0.05$) in Table 4.8.1, attained significance at the lower order of probability of $P \leq 0.09$, further reinforcing the presence of the trend.

The most likely explanation of the increased tiller numbers at D2 compared with D1 may revolve around moisture supplies to the seed. With a mean seeding depth of 20.4mm at D1 (compared with 27.2mm at D2), many of the seeds were quite close to the surface. This would have placed many (at least more than at D2) in a zone of fluctuating soil moisture conditions caused by weather conditions which included windy days interspersed with periodic showers (see Appendix 1 for cumulative moisture balance).

It is possible that the fluctuating soil moisture levels may have been another source of pre-emergent stress to the seedlings at D1 (Benjamin, 1990) which manifested itself in

lower productivity at a later stage of development, although earlier work with the seed groove shape used in this experiment suggested that it maintained a high relative humidity, resulting in an ideal environment for subsurface survival of seedlings (Baker, 1976; Choudhary and Baker, 1980, 1981a,b). This latter suggestion is supported by the fact that none of the emergence parameters measured showed a significant difference between D1 and D2, at least for wheat. It is also possible that lower, more fluctuating levels of moisture may have affected seedling growth at an early stage before the roots could find a more constant supply of moisture slightly deeper in the soil profile. The trend for decreasing tiller numbers with increasing depth from D2 through D4 is not surprising, given that this is also the trend suggested by the majority of reports in the literature.

In this experiment, although the number of seeds per ear did increase slightly with increasing depth (31.8 at D1 up to 36.3 at D4), fertile tiller numbers did not follow the same trend and, as well as this, the increase in number of seeds per ear was counteracted by a corresponding reduction in thousand-seed-weight of harvested seed from the greater depth (Table 4.8.1.1). The number of tillers per plant at D1 and D3 was 1.9, with D2 higher at 2.0 and D4 lower at 1.7. This indicates that the stresses applied to the wheat seedlings, particularly at D4, were of sufficient magnitude to prevent any compensatory increase in tiller numbers, despite the significantly lower plant population at this depth compared with the other three nominal depths. This resulted in the lower yield at D4.

Because of this lack of compensatory growth in terms of weight of grain per ear, the yield figures closely reflect the tiller numbers at each nominal depth. The greater variability in the yield data resulted in a coefficient of variation that was approximately four times that of the tiller population data. This, in turn, meant far less significance in the yield results even though the percentage differences between depths were very similar to those for tiller numbers. This greater variability in yield data may also have been a result of the sampling being dictated to some extent by the degree of rat damage. It is hard to know whether the rats would have randomly pulled over tillers to eat the grain or whether they targeted the larger ears before moving on to the less profitable meals. In any case, some plots were more severely affected than others which led to the increased variability in both yield and thousand-seed-weight data.

5. SUMMARY AND CONCLUSIONS

A quantitative understanding of the degree to which depth-sensitive plant species are likely to react to variations in seeding depth is considered beneficial in attempting to establish design parameters for no-tillage drills with respect to their ability to accurately control depth. This experiment was undertaken in an attempt to gain some data relating variations in seeding depth to plant performance (in terms of various emergence parameters) of wheat and lupin. It was also designed to assess whether or not the addition of soil scrapers to the opener assembly would improve seeding accuracy under the prevailing conditions. A secondary consideration was to see if emergence responses of wheat were carried through to affect yield parameters as well. It is important to note that these results should only be interpreted within the conditions of this experiment and that care should be taken in attempting to extrapolate these results to situations where different species or depth treatments apply, or where soil types or soil/atmospheric environmental conditions other than those that were in evidence in this experiment are being considered. Seed-drill opener types other than that used in this experiment may also produce different results.

The first point to note is that, even with identical depth rack settings on each of the drill openers, the two species were not necessarily sown at the same depth. Lupin tended to be sown deeper than wheat in most cases. Scrapers appeared to have very little effect under the conditions prevailing in this experiment, with second order interactions involving scrapers exhibiting inconsistent relationships. Surprisingly, scrapers had no effect on the variability of seed placement around the mean seeding depth.

The regression coefficients for all the regressions of emergence parameters as a function of seeding depth, for both species, were highly significant. This strongly suggests that the soil environment encountered by the seeds and seedlings at different depths had a significant effect (additional to the emergence depth *per se*) on all of the emergence parameters, although the extent and variability of the responses varied.

In terms of total emergence, wheat was much less affected by seeding depth, and also exhibited a much greater degree of variability around the regression line, than lupin. Lupin emergence dropped by the equivalent of almost 17% for each 10mm increase in seeding depth. This was around four times the response demonstrated by wheat.

Statistically significant reductions in rates of emergence, for those seedlings that did emerge, occurred for both species as seeding depth increased. These reductions in daily rates of emergence were remarkably similar for both species (approximately 1.0%/day for each 10mm increase in depth) although, overall, wheat emerged at twice the rate of lupin. However, even changes in rate of emergence that attained statistical significance appeared not to be of sufficient magnitude to be of any great practical importance under the conditions of this experiment, especially in the case of wheat. This might not be the case under more adverse conditions.

The time taken to reach 5% and 95% emergence followed a strong linear trend of increasing with increasing depth. Lupin was again more affected by depth, with the effect of changes in depth resulting in a delay in days-to-5%-emergence of twice that of wheat. Depth effects on days-to-95%-emergence for lupin were almost three times those of wheat. Correlations between depth of seeding versus actual day of emergence for individual seedlings of both species suggested that only a little over half of the factors contributing to the day of emergence were explainable by a straight line relationship with depth. The much stronger correlation between days-to-5%-emergence and seeding depth on a plot basis, however, illustrated that the variability of this relationship for individual seeds is likely to be a result of factors such as genetic variability in germination time and seed orientation in the slot.

The trend for changes in tiller population and yield of wheat with depth followed closely those of changes in seedling establishment. Tiller numbers were significantly different at all four nominal depths. Although yields were closely related to tiller numbers, greater variability in the yield data meant that a significant reduction occurred only at D4, with all other depths the same. The only difference in harvested seed size was that those from D4 were smaller than those from D1 and D2.

It is evident from the results of this trial that individual species are likely to react quite differently to seeding depth variations under no-tillage. In designing a drill to sow a range of crops it would be logical to base design parameters for depth control mechanisms, as well as other aspects of the machine that affect seed placement accuracy, around the performance of a crop that exhibits a high degree of sensitivity to seeding depth variation. In this trial lupin showed a far greater degree of sensitivity than did wheat with respect to various emergence parameters.

These results could provide an initial guideline regarding the accuracy required of no-tillage drills. The limited range of this experiment in terms of species and soil

conditions studied, however, suggests the need for further research to examine the sensitivity of other crops and/or soil types to changes in depth. Different soil types and conditions might also affect the accuracy with which an opener is able to control accuracy of seed placement. All these considerations need to be addressed to gain a more complete picture of the accuracy required of no-tillage seed-drill openers throughout a wide range of conditions.

6. REFERENCES

- Abrecht, D.G. 1989. No-till crop establishment on red earth soils at Katherine, Northern Territory: effect of sowing depth and firming wheel pressure on the establishment of cowpea, mung bean, soybean and maize. *Aust. J. Exptl. Agric.* 29: 397-402.
- Abrecht, D.G. and Bristow, K.L. 1990. Maize seedling response to the soil environment at varying distances from a bare soil-mulched soil boundary. *Soil Tillage Res.* 15: 205-216.
- Addae, P.C. and Pearson, C.J. 1992. Thermal requirements for germination and seedling growth of wheat. *Aust. J. Agric. Res.* 43: 585-594.
- Addae, P.C., Collis-George, N. and Pearson, C.J. 1991. Over-riding effects of temperature and soil strength on wheat seedlings under minimum and conventional tillage. *Field Crops Res.* 28: 103-116.
- Al-Darby, A.M. and Lowery, B. 1987. Seed zone soil temperature and early corn growth with three conservation tillage systems. *Soil Sci. Soc. Am. J.* 51: 768-774.
- Alessi, J. and Power, J.F. 1971. Corn emergence in relation to soil temperature and seeding depth. *Agron. J.* 63: 717-719.
- All, J.N. and Musick, G.J. 1986. Management of vertebrate and invertebrate pests. pp. 347-387. (In) Sprague, M.A. and Triplett, G.B. (eds.), *No-Tillage and Surface-Tillage Agriculture - The Tillage Revolution*. John Wiley and Sons Inc., New York, N.Y., U.S.A.
- Allen, R.R. 1988. Performance of three wheat seeders in conservation tillage residue. *Appl. Engng Agric.* 4(3): 191-196.
- Allen, R.R., Musick, J.T., Wood, F.O. and Dusek, D.A. 1975. No-till seeding of irrigated sorghum double cropped after wheat. *Trans. ASAE.* 18:1109-1113.
- Allmaras, R.R., Burrows, W.C. and Larson, W.E. 1964. Early growth of corn as affected by soil temperature. *Soil Sci. Soc. Am. Proc.* 28: 272-275.
- Anderson, W.K. 1986. Some relationships between plant population, yield components and grain yield of wheat in a Mediterranean environment. *Aust. J. Agric. Res.* 37: 219-233.
- Anon. 1987. Deutz-Allis Model 385 'Quadra-disk' planter. Deutz-Allis Corporation, Milwaukee, Wisconsin, USA.

- Anon. 1988. Introducing the new 750 All-Till drill. John Deere & Co., Moline, Illinois, U.S.A.
- Army, T.J., Wiese, A.F. and Hanks, R.J. 1961. Effect of tillage and chemical weed control practices on soil moisture losses during the fallow period. *Soil Sci. Soc. Amer. Proc.* 25: 410-413.
- Arndt, W. 1965. The nature of the mechanical impedance to seedlings by soil surface seals. *Aust. J. Soil Research.* 3: 45-54.
- Aston, A.R. and Fischer, R.A. 1986. The effect of conventional cultivation, direct drilling and crop residues on soil temperatures during the early growth of wheat at Murrumbateman, New South Wales. *Aust. J. Soil Res.* 24: 49-60.
- Aulakh, M.S., Rennie D.A. and Paul, E.A. 1984. Gaseous nitrogen losses from soils under zero-till as compared with conventional-till management systems. *J. Environ. Qual.* 13: 130-136.
- Auld, B.A., Kemp, D.R. and Medd, R.W. 1983. The influence of spatial arrangement on grain yield of wheat. *Aust. J. Agric. RES.* 34: 99-108.
- Babowicz, R.J., Hyde, G.M. and Simpson, J.B. 1985. Fertiliser effects under simulated no-tillage conditions. *Trans ASAE.* 28(4): 1003-1006.
- Baker, C.J. 1976. Experiments relating to techniques for direct drilling of seeds into untilled dead turf. *J. Agric. Engng. Res.* 21: 133-145.
- Baker, C.J. and Afzal, C.M. 1986. Dry fertiliser placement in conservation tillage: seed damage in direct drilling (no-tillage). *Soil Tillage Res.* 7: 241-250.
- Baker, C.J. and Choudhary, M.A. 1988. Seed placement and micro-management of residue in dryland no-till. pp. 544-546. (In) *Proc. Intl. Conf. on Dryland Farming.* Texas A.E.S., Amarillo/Bushlands, Texas, USA.
- Baker, C.J. and Desborough, P.J. 1985. Optimising seed placement to maximise seedling emergence in no-tillage. pp. 963-971. (In) *Proc. World Soybean Res. Conf. III.*
- Baker, C.J. and Mai, T.V. 1982. Physical effects of direct drilling equipment on undisturbed soils. 5. Groove compaction and seedling root development. *N.Z. J. Agric. Res.* 25: 51-60.
- Baker, C.J. and Saxton, K.E. 1988. The cross-slot conservation-tillage grain drill opener. *ASAE Paper #88-1568.* ASAE, St. Joseph, Michigan, USA.
- Baker, C.J., Chaudhry, A.D. and Springett, J.A. 1987. Barley seedling establishment and infiltration from direct drilling in a wet soil. *Proc. Agron. Soc. N.Z.* 17: 59-66.

- Baker, C.J., Chaudhry, A.D. and Springett, J.A. 1988. Barley seedling establishment by direct drilling in a wet soil. 3. Comparison of six sowing techniques. *Soil Tillage Res.* 11: 167-181.
- Baker, C.J., McDonald, J.H., Seebeck, K., Rix, C.S. and Griffiths, P.M. 1979. Developments with seed drill coulters for direct drilling. III. An improved chisel coulters with trash handling and fertiliser placement capabilities. *N.Z.J. of Exp. Agric.* 7: 189-196.
- Ball, B.C. and O'Sullivan, M.F. 1982. Soil strength and crop emergence in direct drilled and ploughed cereal seedbeds in seven field experiments. *J. Soil Sci.* 33: 609-622.
- Bauer, A. and Kucera, H.L. 1978. Effect of tillage on some soil physiochemical properties and on annually cropped spring wheat yields. *North Dakota State University A.E.S. Bulletin* 506.
- Benoit, G.R. and Lindstrom, M.J. 1987. Interpreting tillage-residue management effects. *J. Soil Water Conserv.* 42(2): 87-90.
- Benjamin, L.R. 1990. Variation in time of seedling emergence within populations: a feature that determines individual growth and development. *Adv. Agron.* 44: 1-25.
- Berry, W.A.J. and Mallett, J.B. 1988. The effect of tillage: maize residue interactions upon soil water storage. *S. Afr. J. Plant Soil* 5(2): 57-64.
- Berry, W.A.J., Mallett, J.B. and Greenfield, P.L. 1987. Water storage, soil temperatures and maize (*Zea mays* L.) growth for various tillage practices. *S. Afr. J. Plant Soil* 4(1): 26-30.
- Bleasdale, J.K.A. 1984. The importance of crop establishment. pp. 1-11 (In) *Aspects of Applied Biology 7, Crop Establishment: Biological Requirements and Engineering Solutions*. The Association of Applied Biologists, National Vegetable Research Station, Wellesbourne, Warwick, U.K.
- Blevins, R.L. 1984. Soil adaptability for no-tillage. pp. 42-65. (In) Phillips, R.E. and Phillips, S.H. (eds.), *No-Tillage Agriculture - Principles and Practices*. Van Nostrand Reinhold Company, New York, N.Y., U.S.A.
- Blevins, R.L., Cook, D., Phillips, S.H. and Phillips, R.E. 1971. Influence of no-tillage on soil moisture. *Agron. J.* 63: 593-596.
- Bliss, C.I. 1970. *Statistics in Biology. Statistical methods for research in the natural sciences. Vol. II*. McGraw-Hill Book Company, New York, U.S.A.
- Bond, J.J. and Willis, W.O. 1969. Soil water evaporation: surface residue rate and placement effects. *Soil Sci. Soc. Amer. Proc.* 33: 445-448.

- Bond, J.J. and Willis, W.O. 1970. Soil water evaporation: first stage drying as influenced by surface residue and evaporation potential. *Soil Sci. Soc. Amer. Proc.* 34: 924-928.
- Bond, J.J. and Willis, W.O. 1971. Soil water evaporation: long-term drying as influenced by surface residue and evaporation potential. *Soil Sci. Soc. Amer. Proc.* 35: 984-987.
- Boosalis, M.G., Douppnik, B.L. and Watkins, J.E. 1986. Effect of surface tillage on plant diseases. pp. 389-408. (In) Sprague, M.A. and Triplett, G.B. (eds.), *No-Tillage and Surface-Tillage Agriculture - The Tillage Revolution*. John Wiley and Sons Inc., New York, N.Y., U.S.A.
- Bowen, H.D. 1966. Measurement of edaphic factors for determining planter specifications. *Trans. ASAE.* 9: 725-735.
- Brock, J.L. 1973. Effect of sowing depth and post-sowing compaction on the establishment of tall fescue varieties. *N.Z. J. Exptl. Agric.* 1: 11-14.
- Buften, L.P. 1984. The mechanisation of seed sowing. 2. Rowcrops. pp. 117-138. (In) *Aspects of Applied Biology 7, Crop Establishment: Biological Requirements and Engineering Solutions*. The Association of Applied Biologists, National Vegetable Research Station, Wellesbourne, Warwick, U.K.
- Burleigh, J.R., Allan, R.E. and Vogel, O.A. 1965. Varietal differences in seedling emergence of winter wheats as influenced by temperature and depth of plants. *Agron. J.* 57: 195-198.
- Campbell, A.J. 1985. An X-ray technique for determining seed placement in direct-drilled soils. Unpublished M.Phil. thesis, Massey University, Palmerston North, New Zealand.
- Campbell, B.D., McDonald, J.H. and Baker, C.J. 1985. A mechanism to regulate winged coulter depth and overdrilled seed spacing in field experiments. *N.Z. J. Exptl. Agric.* 13: 175-179.
- Cannell, R.Q. 1985. Reduced tillage in North-West Europe - a review. *Soil Tillage Res.* 5: 129-177.
- Carefoot, J.M., Nyborg, M. and Lindwall, C.W. 1990. Tillage-induced soil changes and related grain yield in a semi-arid region. *Can. J. Soil Sci.* 70: 203-214.
- Carter, M.R., Kunelius, H.T., White, R.P. and Campbell, A.J. 1990. Development of direct drilling systems for sandy loam soils in the cool humid climate of Atlantic Canada. *Soil Till. Res.* 16: 371-387.

- Chaudhry, A.D. 1985. Effects of direct drilling opener types, crop residues and earthworms on seed and seedling performance of barley in a wetting soil. PhD Thesis, Massey University Library, Palmerston North, New Zealand.
- Chaudhry, A.D. and Baker, C.J. 1988. Barley seedling establishment by direct drilling in a wet soil. 1. Effects of openers under simulated rainfall and high water-table conditions. *Soil Tillage Res.* 11: 43-61.
- Chaudhry, A.D., Baker, C.J. and Springett, J.A. 1987. Barley seedling establishment by direct drilling in a wet soil. 2. Effects of earthworms, residue and openers. *Soil Tillage Res.* 9: 123-133.
- Choudhary, M.A. 1985. Low risk no-till. pp. 500-507. (In) Proc. Intl. Conf. on Soil Dynamics. Auburn, Alabama, USA.
- Choudhary, M.A. and Baker, C.J. 1980. Physical effects of direct drilling equipment on undisturbed soils. 1. Wheat seedling emergence under controlled climates. *N.Z. J. Agric. Res.* 23: 489-496.
- Choudhary, M.A. and Baker, C.J. 1981a. Physical effects of direct drilling equipment on undisturbed soils. 2. Seed groove formation by a "triple disc" coulter and seedling performance. *N.Z. J. Agric Res.* 24: 183-187.
- Choudhary, M.A. and Baker, C.J. 1981b. Physical effects of direct drilling equipment on undisturbed soils. 3. Wheat seedling performance and in-groove micro-environment in a dry soil. *N.Z. J. Agric. Res.* 24: 189-195.
- Choudhary, M.A. and Baker, C.J. 1982. Effects of drill coulter design and soil moisture status on emergence of wheat seedlings. *Soil Till. Res.* 2: 131-142.
- Choudhary, M.A., Baker, C.J. and Stiefel, W. 1988. Dry fertiliser placement in direct drilling. *Soil Till. Res.* 12: 213-221.
- Choudhary, M.A., Guo Pei Yu and Baker, C.J. 1985. Seed placement effects on seedling establishment in direct-drilled fields. *Soil Till. Res.* 6: 79-93.
- Collis-George, N. and Hector, J.B. 1966. Germination of seeds as influenced by matric potential and by area of contact between seed and soil water. *Aust. J. Soil Res.* 4: 145-164.
- Collis-George, N. and Yoganathan, P. 1985a. The effect of soil strength on the germination and emergence of wheat (*Triticum aestivum* L). 1. Low shear strength conditions. *Aust J. Soil Res.* 23: 577-587.
- Collis-George, N. and Yoganathan, P. 1985b. The effect of soil strength on the germination and emergence of wheat (*Triticum aestivum* L). 2. High shear strength conditions. *Aust J. Soil Res.* 23: 589-601.

- Colvin, T.S., Laflen, J.M. and Erbach, D.C. 1981. A review of residue reduction by individual tillage implements. pp.102-110. (In) Crop Production with Conservation in the 80's. ASAE, St. Joseph, Michigan, USA.
- Cook, R.J and Haglund, W.A. 1991. Wheat yield depression associated with conservation tillage caused by root pathogens in the soil not phytotoxins from the straw. Soil Biol. Biochem. 23(12): 1125-1132.
- Cook, R.J. and Murray, T.D. 1987. Management of soilborne pathogens of wheat in soil conservation systems. pp. 314-323. (In) STEEP - Conservation Concepts and Accomplishments. Washington State University Press, Pullman, Washington, USA.
- Crosson, P. 1985. Impact of erosion on land productivity and water quality in the United States. pp. 217-236. (In) Soil Erosion and Conservation. Soil Conserv. Soc. Am. Press, Ankeny, Iowa, USA.
- Crosson, P., Hanthorn, M. and Duffy, M. 1986. The economics of conservation tillage. pp. 409-436. (In) Sprague, M.A. and Triplett, G.B. (eds.), No-Tillage and Surface-Tillage Agriculture - The Tillage Revolution. John Wiley and Sons Inc., New York, N.Y., U.S.A.
- Currie, J.A. 1984. The physical environment in the seedbed. pp. 33-54. (In) Aspects of Applied Biology 7, Crop Establishment: Biological Requirements and Engineering Solutions. The Association of Applied Biologists, National Vegetable Research Station, Wellesbourne, Warwick, U.K.
- Deibert, E.J. 1990. Evaluation of new seed opener concepts with different seedbed environments. pp. 85-89. (In) Proc. Great Plains Cons. Till. Symp. Great Plains Agricultural Council Bull. #131.
- Deibert, E.J., Utter, R.A. and Schwert, D.P. 1991. Tillage system influence on earthworms (*Lumbricidae*) in North Dakota. North Dakota Farm Res. 48(5): 10-12.
- de Jong, R. and Best, K.F. 1979. The effect of soil water potential, temperature and seeding depth on seedling emergence of wheat. Can. J. Soil Sci. 59: 259-264.
- Dixon, H.N. 1972. The effects of coulter design on soil compaction and root development of a cereal following direct drilling. Unpublished B Agr Sc (Hons) project (Agr Machinery). Massey University, Palmerston North, N.Z.
- Dubetz, S., Russell, G.C. and Anderson, D.T. 1962. Effect of soil temperature on seedling emergence. Can. J. Plant Sci. 42: 481-487.
- Dungan, G.H., Lang, A.L. and Pendleton, J.W. 1958. Corn plant population in relation to soil productivity. Adv. Agron. 10: 435-473.

- Eagles, H.A. 1987. Population responses of maize hybrids in the Manawatu. Proc. Agron. Soc. N.Z. 17: 1-6.
- Edwards, C.A. 1975. Effects of direct drilling on the soil fauna. Outlook Agric. 8: 243-244.
- Edwards, W.M. 1982. Predicting tillage effects on infiltration. pp. 105-115. (In) Predicting Tillage Effects on Soil Physical Properties and Processes. ASA Spec. Pub. #44. ASA, SSSA, Madison, Wisconsin, USA.
- Ehlers, W. 1975. Observations on earthworm channels and infiltration on tilled and untilled loess soil. Soil Sci. 119: 242-249.
- Elliot, L.F. and Lynch, J.M. 1984. Pseudomonads as a factor in the growth of winter wheat (*Triticum aestivum* L). Soil Biol. Biochem. 16(1): 69-71.
- Epstein, E. and Grant, W.J. 1971. Soil erodibility as affected by soil surface properties. Trans. ASAE. 14(4): 647-648, 655.
- Erbach, D.C. 1981. Planting for crop production with conservation. pp. 50-65. (In) Crop Production with Conservation in the 80's. ASAE Publ. 7-81, St. Joseph, Michigan, USA.
- Erbach, D.C., Morrison, J.E., Jr. and Wilkins, D.E. 1983. Equipment modification and innovation for conservation tillage. J. Soil Water Conserv. 38(3): 182-185.
- Felsot, A.S., Welch, L.F., Curran, W.S., Knake, E.L. and Ruesink, W.G. 1988. Effects of agrochemicals in conservation tillage on the environment. Illinois Res. 30(3/4): 11-15.
- Follas, G.B. 1982. A study of the effects of ground cover on overwintering slug populations and the effect of coulter design on slug incidence in direct drilling. Unpublished M.Agr.Sc. Thesis. Massey University Library, Palmerston North, N.Z.
- Foster, G.R. and Moldenhauer, W.C. 1985. Tillage characteristics affecting soil erosion by water. pp. 536-548. Vol. 3. (In) Proc. Int. Conf. on Soil Dynamics. Auburn, Alabama, USA.
- Fowler, D.B. 1990. Stubble management and no-till winter wheat seedling establishment. pp. 55-64. (In) Conservation Tillage: Proc. Great Plains Conservation Tillage Symposium. Great Plains Agricultural Council Bulletin #131.
- Fox, R.H. and Bandel, V.A. 1986. Nitrogen utilisation with no-tillage. pp. 117-148. (In) Sprague, M.A. and Triplett, G.B. (eds.), No-Tillage and Surface-Tillage Agriculture - The Tillage Revolution. John Wiley and Sons Inc., New York, N.Y., U.S.A.

- Frederick, J.R. and Marshall, H.G. 1985. Grain yield and yield components of soft red winter wheat as affected by management practices. *Agron. J.* 77: 495-499.
- Fredrickson, J.K., Elliot, L.F. and Engibous, J.C. 1987. Crop residues as substrate for host-specific inhibitory pseudomonads. *Soil Biol. Biochem.* 19(2): 127-134.
- Frengley, G.A.G. 1983. Economic benefits of conservation tillage in New Zealand. 1. Mixed crop and livestock farms. *Soil Tillage Res.* 3: 347-356.
- Frye, W.W. 1984. Energy requirements in no-tillage. pp. 127-151. (In) Phillips, R.E. and Phillips, S.H. (eds.), *No-Tillage Agriculture - Principles and Practices*. Van Nostrand Reinhold Company, New York, N.Y., U.S.A.
- Fryrear, D.W. 1985. Soil cover and wind erosion. *Trans. ASAE.* 28(3): 781-784.
- Gallaher, R.N. and Ferrer, M.B. 1987. Effect of no-tillage vs. conventional tillage on soil organic matter and nitrogen contents. *Commun. in Soil Sci. Plant Anal.* 18(9): 1061-1076.
- Gantzer, C.J. and Blake, G.R. 1978. Physical characteristics of Le Sueur clay loam following no-till and conventional tillage. *Agron. J.* 70(5): 853-857.
- Gill, K.S. and Prihar, S.S. 1989. Seedling emergence from a two-layered seed zone: seeding depth and position, crop species and initial soil moisture effects. *Seed Sci. and Technol.* 17: 73-82.
- Gomez, K.A. and Gomez, A.A. 1984. *Statistical Procedures for Agricultural Research*. 680 pp. Wiley-Interscience, New York, U.S.A.
- Goodman, S.M. and Scott, W.R. 1985. Seedling emergence of wheat as affected by sowing depth, seed size and sowing date. *Proc. Agron. Soc. N.Z.* 15: 65-69.
- Goss, M.I. 1989. Leaching of nitrate under arable crops. *Agric. Engineer.* Autumn 1989: 90-92.
- Graven, L.M. and Carter, P.R. 1990. Seed size/shape and tillage system effect on corn growth and grain yield. *J. Prod. Agric.* 3(4): 445-452.
- Griffith, D.R., Mannering, J.V. and Box, J.E. 1986. Soil and moisture management with reduced tillage. pp. 19-57. (In) Sprague, M.A. and Triplett, G.B. (eds.), *No-Tillage and Surface-Tillage Agriculture - The Tillage Revolution*. John Wiley and Sons Inc., New York, N.Y., U.S.A.
- Gupta, S.C., Larsen, W.E. and Linden, D.R. 1983. Tillage and surface residue effects on soil upper boundary temperatures. *Soil Sci. Soc. Am. J.* 47:1212-1218.

- Gupta, S.C., Schneider, E.C. and Swan, J.B. 1988. Planting depth and tillage interactions on corn emergence. *Soil Sci. Soc. Am. J.* 52: 1122-1127.
- Gul, A. and Allan, R.E. 1976. Stand establishment of wheat lines under different levels of water potential. *Crop Sci.* 16: 611-615.
- Hadjichristodoulou, A., Della, A. and Photiades, J. 1977. Effect of sowing depth on plant establishment, tillering capacity and other agronomic characters of cereals. *J. Agric. Sci., Camb.* 89: 161-167.
- Hallberg, G.R. 1986. From hoes to herbicides; agriculture and groundwater quality. *J. Soil and Water Conserv.* 41: 357-363.
- Hamblin, A.P. 1984. The effect of tillage on soil surface properties and the water balance of a xeralfic alfisol. *Soil Till. Res.* 4: 543-559.
- Hampton, J.G. 1981. Effect of ear populations on wheat production in the Manawatu and Rangitikei. *N.Z. J. Exp. Agric.* 9: 199-202.
- Hampton, J.G., McCloy, B.L. and McMillan, D.R. 1981. Ear populations and wheat production. *N.Z. J. Exp. Agric.* 9: 185-189.
- Hart, J. 1964. Wide choice in wheat and barley planting depth. *Queensland Agr. J.* 90(3): 137-138.
- Hegarty, T.W. 1984. The influence of environment on seed germination. pp. 13-31. (In) *Aspects of Applied Biology 7, Crop Establishment: Biological Requirements and Engineering Solutions*. The Association of Applied Biologists, National Vegetable Research Station, Wellesbourne, Warwick, U.K.
- Herbek, J.H., Murdock, L.W. and Blevins, R.L. 1986. Tillage system and date of planting effects on yield of corn on soils with restricted drainage. *Agron. J.* 78: 824-826.
- House, G.J. and Parmalee, R.W. 1985. Comparison of soil arthropods and earthworms from conventional and no-tillage agroecosystems. *Soil Till. Res.* 5: 351-360.
- Hucl, P. and Baker, R.J. 1990. Effect of seeding depth and temperature on tillering characteristics of four spring wheat cultivars. *Can. J. Plant Sci.* 70: 409-417.
- Hughes, K.A. 1975. A study of tillage mechanisms in relation to soil properties and crop growth. Unpublished M.Agr.Sc. Thesis, Massey University, Palmerston North, New Zealand.
- Hughes, K.A. and Mitchel, W.J.P. 1987. The relationship of coleoptile length and plant height with establishment of cereals under zero-tillage. *Proc. Agron. Soc. N.Z.* 17: 67-70.

- Hyde, G.M., Wilkins, D.E., Saxton, K.E., Hammel, J., Swanson, G., Hermanson, R., Dowding, E.A., Simpson, J.B. and Peterson, C.L. 1987. Reduced tillage seeding equipment development. (In) Elliot, L.F. (ed): STEEP - Conservation Concepts and Accomplishments. Washington State University Press, Pullman, Washington, USA.
- Jafari, J.V. and Fornstrom, K.J. 1972. A precision punch planter for sugar beets. *Trans. ASAE* 15: 569-571.
- Johnson, M.D. and Lowery, B. 1985. Effect of three conservation tillage practices on soil temperature and thermal properties. *Soil Sci. Soc. Am. J.* 49: 1547-1552.
- Johnstone, J.V., Wilson, D.R., Martin, R.J., Gillespie, R.N. and McCloy, B.L. 1990. Establishment, sowing time and plant population effects on CRD Otane wheat. *Proc. Agron. Soc. N.Z.* 20: 103-109.
- Kaspar, T.C., Erbach, D.C. and Cruse, R.M. 1990. Corn response to seed-row residue removal. *Soil Sci. Soc. Amer. J.* 54: 1112-1117.
- Kaufmann, M.L. 1968. Coleoptile length and emergence in varieties of barley, oats and wheat. *Can. J. Plant Sci.* 48: 357-361.
- Kirby, E.J.M. 1967. The effect of plant density upon the growth and yield of barley. *J. Agric. Sci. Camb.* 68: 317-324.
- Klepper, B.L., Rickman, R.W. and Chevalier, P.M. 1987. Wheat plant growth in conservation tillage. pp. 93-107. (In) STEEP - Conservation Concepts and Accomplishments. Washington State University Press, Pullman, Washington, USA.
- Klute, A. 1982. Tillage effects on the hydraulic properties of soil: A review. pp. 29-44. (In) *Predicting Tillage Effects on Soil Physical Properties and Processes*. ASA Spec. Pub. #44. ASA, SSSA, Madison, Wisconsin, USA.
- Knight, R. 1983. Some factors causing variation in the yield of individual plants of wheat. *Aust. J. Agric. Res.* 34: 219-228.
- Koronka, P. 1973. Machinery development for direct drilling. *Outlook on Agric.* 7(4): 190-195.
- Laflen, J.M. and Colvin, T.S. 1981. Effect of crop residue on soil loss from continuous row cropping. *Trans. ASAE.* 24(3): 605-609.
- Laflen, J.M., Moldenhauer, W.C. and Colvin, T.S. 1981. Conservation tillage and soil erosion on continuously rowcropped land. (In) *Crop Production with Conservation in the 80's*. ASAE., St. Joseph, Michigan, USA.

- Lafond, G.P and Baker, R.J. 1986. Effects of temperature, moisture stress and seed size on germination of nine spring wheat cultivars. *Crop Sci.* 26: 563-567.
- Lafond, G.P. and Fowler D.B. 1989a. Soil temperature and moisture stress effects on kernel water uptake and germination of winter wheat. *Agron. J.* 81: 447-450.
- Lafond, G.P. and Fowler D.B. 1989b. Soil temperature, water content, seeding depth and simulated rainfall effect on winter wheat emergence. *Agron. J.* 81: 609-614.
- Lal, R. 1976. No-tillage effects on soil properties under different crops in western Nigeria. *Soil Sci. Soc. Amer. J.* 40: 762-768.
- Lal, R. 1978. Influence of within- and between-row mulching on soil temperature, soil moisture, root development and yield of maize in a tropical soil. *Field Crops Res.* 1: 127-139.
- Lal, R. 1985. Mechanised tillage systems effects on properties of a tropical alfisol in watersheds cropped to maize. *Soil Till. Res.* 6: 149-161.
- Lal, R. and van Doren, D.M., Jr. 1990. Influence of 25 yrs of continuous corn production by three tillage methods on water infiltration for two soils in Ohio. *Soil Till. Res.* 16: 71-84.
- Lal, R., De Vleeschauwer, D. and Malafa Nganje, R. 1980. Changes in properties of a newly cleared tropical alfisol as affected by mulching. *Soil Sci. Soc. Amer. J.* 44: 827-832.
- Lal, R., Eckert, D.J. and Logan, T.J. 1988. Environmentally sustainable dryland farming systems. pp. 661-667. (In) P.W.Unger and others (eds), *Challenges in Dryland Agriculture - A Global Perspective*. Conf. Proc. Amarillo/Bushlands, Texas, USA.
- Lattanzi, A.R., Meyer, L. D. and Baumgardner, M.F. 1974. Influences of mulch rate and slope steepness on interrill erosion. *Soil Sci. Soc. Amer. Proc.* 38: 946-950.
- Lessiter, F. 1992. Acreage Survey (1991-1992). *No-Till Farmer*: Jan. 1992.
- Letey, J. 1985. Relationship between soil physical properties and crop production. *Adv. Soil Sci.* 1: 277-294.
- Linden, D.R. 1982. Predicting tillage effects on evaporation from the soil. pp. 117-132. (In) Unger, P.W. and others (eds.). *Predicting tillage effects on soil physical properties and processes*. ASA Special Publication #44. Madison, Wisconsin, USA.

- Lindstrom, M.J. and Forcella, F. 1988. Tillage and residue management effects on crop production in the Northwestern Corn Belt. pp. 565-567. (In) P.W.Unger and others (eds), Challenges in Dryland Agriculture - A Global Perspective. Conf. Proc. Amarillo/Bushlands, Texas, USA.
- Lindstrom, M.J., Papendick, R.I. and Koehler, F.E. 1976. A model to predict winter wheat emergence as affected by soil temperature, water potential and depth of planting. *Agron. J.* 68: 137-140.
- Lindwall, C.W. and Anderson, D.T. 1977. Effects of different seeding machines on spring wheat production under various conditions of stubble residue and soil compaction in no-till rotations. *Can. J. Soil Sci.* 57: 81-91.
- Lindwall, C.W. and Erbach, D.C. 1983. Residue cover, soil temperature regime and corn growth. Paper #83-1024, Presented at the 1983 summer meeting of the ASAE.
- Little, C.E. 1987. *Green Fields Forever - The conservation tillage revolution in America.* Island Press, Washington, D.C., USA.
- Loeppky, H., Lafond, G.P. and Fowler, D.B. 1989. Seeding depth in relation to plant development, winter survival and yield of no-till winter wheat. *Agron. J.* 81: 125-129.
- Logan, T.J., Eckert, D.J., Harrison, B., Beak, D. and Adewumni, J. 1989. Effects of no-till and fall plowing on pesticide movement in runoff and tile drainage. Great Lakes National Program Office: Project No. R005970-01.
- Lopez-Bellido, L. and Fuentes, M. 1986. Lupin crop as an alternative source of protein. *Adv. Agron.* 40: 239-295.
- Lynch, J.M. 1978. Production and phytotoxicity of acetic acid in anaerobic soils containing plant residues. *Soil Biol. Biochem.* 10: 131-135.
- McCown, R.L., Peake, D.C.I. and Jones, R.K. 1981. No-tillage tropical legume ley farming research in Northern Australia. pp. 239-247. (In) Proc. Conservation Tillage Seminar, Christchurch, N.Z.
- McGregor, K.C., Greer, J.D. and Gurley, G.E. 1975. Erosion control with no-till cropping practices. *Trans. ASAE.* 18: 918-920.
- Mai, T.V. 1978. The effects of drill coulter designs on soil physical properties and plant responses in untilled seedbeds. Unpublished PhD thesis. Massey University Library, Palmerston North, N.Z.
- Mangold, G. 1992. CRM Acres Climb - No-till posts biggest growth of crop residue management practices. *Soybean Digest*, December 1992: 40-41.

- Mannering, J.V. and Meyer, L.D. 1963. The effects of various rates of surface mulch on infiltration and erosion. *Soil Sci. Soc. Amer. Proc.* 27(1): 84-86.
- Martin, P.M. and Kelleher, F.M. 1984. Effects of row spacing and plant population on sweet sorghum yield. *Aust. J. Exp. Agric. Anim. Husband.* 24: 386-390.
- Martin, J.H., Leonard, W.H. and Stamp, D.L. 1976. *Principles of Field Crop Production.* Macmillan Publishing Co., Inc., New York, U.S.A.
- Maurya, P.R. 1986. Effect of tillage and residue management on maize and wheat yield and on physical properties of an irrigated sandy loam soil in northern Nigeria. *Soil Till. Res.* 8: 161-170.
- Meyer, L.D., Wischmeier, W.H. and Foster, G.R. 1970. Mulch rates required for erosion control on steep slopes. *Soil Sci. Soc. Amer. Proc.* 34: 928-931.
- Millner, J.P. 1983. Agronomy of barley production. pp.53-59. (In) *Barley: Production and Marketing.* Agron. Soc. N.Z. Spec. Pubn. #2.
- Mock, J.J. and Erbach, D.C. 1977. Influence of conservation tillage environments on growth and productivity of corn. *Agron. J.* 69(3): 337-340.
- Moore, D.S. and McCabe, G.P. 1989. *Introduction to the Practice of Statistics.* W.H. Freeman & Company, USA.
- Morrison, J.E., Jr. 1978. No-tillage experimental planter performance and depth regulation evaluation. *Trans. ASAE* 21: 602-604, 609.
- Morrison, J.E., Jr. 1988a. Interactive planter depth control and pneumatic downpressure system. *Trans. ASAE* 31(1): 14-18.
- Morrison, J.E., Jr. 1988b. Hydraulic downpressure system performance for conservation planting machines. *Trans. ASAE* 31(1): 19-23.
- Morrison, J.E., Jr. 1989. Factors affecting plant establishment with a no-tillage planter opener. *Appl. Eng. in Agric.* 5(3): 316-318.
- Morrison, J.E., Jr. and Abrams, C.F., Jr. 1978. Conservation-tillage opener for planters and transplanters. *Trans. ASAE* 21: 843-847.
- Morrison, J.E., Jr. and Gerik, T.J. 1983. Flexible mounted double-discs for conservation planters. *Trans. ASAE* 26: 1044-1045.
- Morrison, J.E., Jr. and Gerik, T.J. 1985a. Planter depth control: 1. Predictions and predicted effects on crop emergence. *Trans. ASAE* 28(5): 1415-1418.
- Morrison, J.E., Jr. and Gerik, T.J. 1985b. Planter depth control: 2. Empirical testing and plant responses. *Trans. ASAE* 28(6): 1744-1748.

- Morrison, J.E., Jr., Allen, R.R., Wilkins, D.E., Powell, G.M., Grisso, R.D., Erbach, D.C., Herndon, L.P., Murray, D.L., Formanek, G.E., Pfost, D.L., Herron, M.M., and Baumert, D.J. 1988. Conservation planter, drill and air-type seeder selection guideline. *Appl. Engng. Agric.* 4(4): 300-309.
- Morrison, J.E., Jr., Gerik, T.J. and Chichester, F.W. 1985. No-tillage system for high-clay soils. pp. 1055-1069. (In) *Proc. Intl. Conf. on Soil Dynamics, Vol. 5: Traction and Transport as Related to Cropping Systems.* Auburn, Alabama, USA.
- Morrison, J.E., Jr., Gerik, T.J., Chichester, F.W., Martin, J.R. and Chandler, J.M. 1990. A no-tillage farming system for clay soils. *J. Prod. Agric.* 3: 219-227.
- Morton, C.T. and Buchele, W.F. 1960. Emergence energy of plant seedlings. Seed environment essential for maximum emergence of seedlings. *Agric. Engg.* 41: 428-431, 453-455.
- Munawar, A., Blevins, R.L., Frye, W.W. and Saul, M.R. 1990. Tillage and cover crop management for soil water conservation. *Agron. J.* 82: 773-777.
- Mutchler, C.K. and Greer, J.D. 1984. Reduced tillage for soybeans. *Trans. ASAE.* 27: 1364-1369.
- Nafziger, E.D., Carter, P.R. and Graham, E.E. 1991. Response of corn to uneven emergence. *Crop Sci.* 31(3): 811-815.
- Norwood, C.A., Schlegel, A.J., Morishita, D.W. and Gwin, R.E. 1990. Cropping system and tillage effects on available soil water and yield of grain sorghum and winter wheat. *J. Prod. Agric.* 3: 356-362.
- Nyborg, M. and Malhi, S.S. 1989. Effect of zero and conventional tillage on barley yield and nitrate nitrogen content, moisture and temperature of soil in north-central Alberta. *Soil Tillage Res.* 15: 1-9.
- Özmerzi, A. 1986. Seed distribution performance of the furrow openers used on drill machines. *Agr. Mech. in Asia, Africa and Latin America.* 17(2): 32-34.
- PAMI. 1985. Evaluation report #420. Prairie Agricultural Machinery Institute, Humboldt, Saskatchewan, Canada.
- PAMI. 1986. Evaluation report #487. Prairie Agricultural Machinery Institute, Humboldt, Saskatchewan, Canada.
- PAMI. 1987. Evaluation report #519. Prairie Agricultural Machinery Institute, Humboldt, Saskatchewan, Canada.
- PAMI. 1988. Choosing the right seeding and fertilising equipment. *Gleanings #558.* Prairie Agricultural Machinery Institute, Humboldt, Saskatchewan, Canada.

- Papendick, R.I. and Campbell, G.S. 1988. Concepts and management strategies for water conservation in dryland farming. pp. 119-127. (In) Proc. Int. Conf. on Dryland Farming. Amarillo/Bushlands A.E.S., Texas, USA.
- Parker, J.J., Jr. and Taylor, H.M. 1965. Soil strength and seedling emergence relations. 1. Soil type, moisture tension, temperature and planting depth effects. *Agron. J.* 57: 289-291.
- Patterson, D.E. 1984. The mechanisation of seed sowing. 1. Cereal crops. pp. 103-115. (In) *Aspects of Applied Biology 7, Crop Establishment: Biological Requirements and Engineering Solutions*. The Association of Applied Biologists, National Vegetable Research Station, Wellesbourne, Warwick, U.K.
- Patterson, D.E., Chamen, W.C.T. and Richardson, C.D. 1980. Long-term experiments with tillage systems to improve the economy of cultivations for cereals. *J. Agric. Eng. Res.* 25: 1-35.
- Payton, D.M., Hyde, G.M. and Simpson, J.B. 1985. Equipment and methods for no-tillage wheat planting. *Trans. ASAE* 28(5): 1419-1424, 1429.
- Pellow, R. 1992. The potential for transplanting seedlings by no-tillage. Unpublished Dip. Agr. Sc. Thesis. Massey University, Palmerston North, New Zealand.
- Perry, D.A. 1984. Factors influencing the establishment of cereal crops. pp. 65-83. (In) *Aspects of Applied Biology 7, Crop Establishment: Biological Requirements and Engineering Solutions*. The Association of Applied Biologists, National Vegetable Research Station, Wellesbourne, Warwick, U.K.
- Phillips, S.H. 1984a. Introduction. pp. 1-10. (In) Phillips, R.E. and Phillips, S.H. (eds.), *No-Tillage Agriculture - Principles and Practices*. Van Nostrand Reinhold Company, New York, N.Y., U.S.A.
- Phillips, S.H. 1984b. Other pests in no-tillage and their control. pp. 171-189. (In) Phillips, R.E. and Phillips, S.H. (eds.), *No-Tillage Agriculture - Principles and Practices*. Van Nostrand Reinhold Company, New York, N.Y., U.S.A.
- Phillips, R.E., Blevins, R.L., Thomas, G.W., Frye, W.W. and Phillips, S.H. 1980. No tillage agriculture. *Science* 208: 1108-1113.
- Photiades, I. and Hadjichristodoulou, A. 1984. Sowing date, sowing depth, seed rate and row spacing of wheat and barley under dryland conditions. *Field Crops Res.* 9: 151-162.
- Power, J.F. and Doran, J.W. 1988. Role of crop residue management in nitrogen cycling and use. pp. 101-113. (In) *Cropping Strategies for Efficient Use of Water and Nitrogen*. Special Pub. #51, ASA-CSSA-SSSA, Madison, Wisconsin, USA.

- Power, J.F., Doran, J.W. and Wilhelm, W.W. 1986. Uptake of nitrogen from soil, fertiliser and crop residues by no-till corn and soybean. *Soil Sci. Soc. Am. J.* 50: 137-142.
- Prasad, R. and Power, J.F. 1992. Crop residue management. *Adv. in Soil Sci.* 18: 205-251.
- Radford, B.J. 1986. Effect of a press wheel and depth of sowing on the establishment of semidwarf and tall wheats. *Aust. J. Exp. Agric.* 26: 697-702.
- Radford, B.J. 1987. Effect of cultivar and temperature on the coleoptile length and establishment of barley. *Aust. J. Exp. Agric.* 27: 313-316.
- Radford, B.J., and Wildermuth, G.B. 1987. Effect of sowing depth, seed dressings, a press wheel, cultivars and trifluralin on the establishment of barley. *Aust. J. Exp. Agric.* 27: 579-584.
- Radford, B.J., Strong, W.M. and Wildermuth, G.B. 1989. Effects of urea and flutriafol on germination, coleoptile length and establishment of wheat and barley. *Aust. J. Exp. Agr.* 29: 551-557.
- Rathore, T.R., Childyal, B.P. and Sachan, R.S. 1981. Germination and emergence of soybeans under crusted soil conditions. 1. Effect of crust impedance to seedling emergence. *Plant Soil.* 62: 97-105.
- Rice, C.W. and Smith, M.S. 1984. Short-term immobilisation of fertiliser nitrogen at the surface of no-till and plowed soil. *Soil Sci. Soc. Am. J.* 48: 295-297.
- Ritchie, W.R. 1982. Aspects of seed transfer with a direct drilling coulter (opener). MAgSc Thesis. Massey University Library, Palmerston North, New Zealand.
- Roebuck, J.F. and Trenerry, J. 1978. Seed size and sowing depth in spring barley. *Exptl. Husb.* 34: 12-18.
- Roth, G.W., Marshall, H.G., Hatley, O.E. and Hill, R.R., Jr. 1984. Effect of management practices on grain yield, test weight, and lodging of soft red winter wheat. *Agron. J.* 76: 379-383.
- Russelle, M.P. and Bolton, F.E. 1980. Soil temperature effects on winter wheat and winter barley emergence in the field. *Agron. J.* 72: 823-827.
- Saxton, K.E., Bristow, K.L., Flerchinger, G.N. and Omer, M.A. 1988. Tillage and crop residue management for water conservation. pp. 493-497. (In) *Proc. Int. Conf. on Dryland Farming*. Amarillo/Bushlands A.E.S., Texas, USA.
- Schaaf, D.E., Hann, S.A. and Lindwall, C.W. 1981. Performance evaluation on furrow openers, cutting coulters and press wheels for seed drills. pp. 76-84. (In) *Crop Production with Conservation in the 80's*. ASAE Pubn. 7-81, St. Joseph, Michigan, USA.

- Sepaskhah, A.R. and Raessi Ardekani, E. 1978. Effect of soil matric potential and seeding depth on emergence of barley. *Agron. J.* 70: 728-731.
- Siddoway, F.H., Chepil, W.S. and Armbrust, D.V. 1965. Effect of kind, amount and placement of residue on wind erosion control. *Trans. ASAE.* 8: 327-331.
- Skidmore, E.L. 1988. Coping with the wind. pp. 104-106. (In) *Proc. Int. Conf. on Dryland Farming.* Texas AES., Amarillo/Bushlands, USA.
- Soento and Donald, C.M. 1980. Emergence, growth and dominance in drilled and square-planted barley crops. *Aust. J. Agric. Res.* 31: 455-470.
- Sprague, M.A. 1986. Overview. pp. 1-18. (In) Sprague, M.A. and Triplett, G.B. (eds.), *No-Tillage and Surface-Tillage Agriculture - The Tillage Revolution.* John Wiley and Sons Inc., New York, N.Y., U.S.A.
- Steel R.G.D. and Torrie. J.H. 1960. *Principles and Procedures of Statistics - with special reference to the biological sciences.* McGraw-Hill Book Company, Inc., New York, U.S.A.
- Stickler, F.C. 1962. Seeding depth and use of press wheels as factors affecting winter barley and winter wheat yields in Kansas. *Agron. J.* 54: 492-494.
- Stoskopf, N.C. 1981. *Understanding Crop Production.* Reston Publishing Company, Inc. Reston, Virginia, U.S.A.
- Stroo, H.F., Elliott, L.F. and Papendick, R.I. 1988. Growth, survival and toxin production of root-inhibitory pseudomonads on crop residues. *Soil Biol. Biochem.* 20(2): 201-207.
- Sunderman, D.W. 1964. Seedling emergence of winter wheats and its association with depth of sowing, coleoptile length under various conditions, and plant height. *Agron. J.* 56: 23-25.
- TeKrony, D.M. and Egli, D.B. 1991. Relationship of seed vigour to crop yield: a review. *Crop Sci.* 31(3): 816-822.
- Tessier, S., Hyde, G.M., Papendick, R.I. and Saxton, K.E. 1991a. No-till seeders effects on seed zone properties and wheat emergence. *Trans ASAE* 34(3): 733-739.
- Tessier, S., Saxton, K.E., Papendick, R.I. and Hyde, G.M. 1991b. Zero-tillage furrow opener effects on seed environment and wheat emergence. *Soil Till. Res.* 21: 347-360.
- Thompson, J.P. 1992. Soil biotic and biochemical factors in a long-term tillage and stubble management experiment on a versitol. 2. Nitrogen deficiency with zero tillage and stubble retention. *Soil Till. Res.* 22: 339-361.

- Triplett, G.B. and Worsham, A.D. 1986. Principles of weed management with surface tillage systems. pp. 319-346. (In) Sprague, M.A. and Triplett, G.B. (eds.), *No-Tillage and Surface-Tillage Agriculture - The Tillage Revolution*. John Wiley and Sons Inc., New York, N.Y., U.S.A.
- Unger, P.W. 1986. Wheat residue management effects on soil water storage and corn production. *Soil Sci. Soc. Am. J.* 50: 764-770.
- Unger, P.W. 1990. Conservation tillage systems. *Adv. in Soil Sci.* 13: 27-68.
- Unger, P.W. and Jones, O.R. 1989. Effective tillage practices for conserving soil and water resources. pp. 161-171. (In) *Management of Versitols for Improved Agricultural Production*. ICRISAT.
- Unger, P.W., and McCalla, T.M. 1980. Conservation tillage systems. *Adv. in Agron.* 33: 1-58.
- Unger, P.W. and Parker, J.J. 1976. Evaporation reduction from soil with wheat, sorghum and cotton residues. *Soil Sci. Soc. Amer. J.* 40: 938-942.
- Van Doren, D.M., Jr., Moldenhauer, W.C. and Triplett, G.B., Jr. 1984. Influence of long-term tillage and crop rotation on water erosion. *Soil Sci. Soc. Amer. J.* 48: 636-640.
- Van Doren, D.M., Jr., Triplett, G.B., Jr. and Henry, J.E. 1976. Influence of long term tillage, crop rotation and soil type combinations on corn yield. *Soil Sci. Soc. Am. J.* 40: 100-105.
- Wade, L.J. and Douglas, A.C.L. 1990. Effect of plant density on grain yield and yield stability of sorghum hybrids differing in maturity. *Aust. J. Exp. Agric.* 30: 257-264.
- Walker, D.J., Young, D.L., Fosberg, M.A., Busacca, A.J., Saxton, K.E., Carter, D.L. and Frazier, B.E. 1987. Long term productivity benefits of soil conservation. pp. 9-40. (In) *STEEP - Conservation Concepts and Accomplishments*. WSU Press, Pullman, Washington, USA.
- Wangdi, K., McKenzie, B.A. and Hill, G.D. 1990. Field establishment of Russell lupin. *Proc. Agron. Soc. N.Z.* 20: 29-35.
- Ward, L.D., Norris, C.P. and Thomas, E.C. 1991. Component interactions in zero-till planters for heavy clay soils of southern Queensland. *Soil Till. Res.* 20: 19-32.
- Whan, B.R. 1976. The emergence of semidwarf and standard wheats and its association with coleoptile length. *Aust. J. Exp. Agric. Anim. Husb.* 16: 411-416.

- White, P.F. and Robson, A.D. 1989. Emergence of lupins from a hard setting soil compared with peas, wheat and medic. *Aust. J. Agric. Res.* 40: 529-537.
- Wilkins, D.E., Muilenberg, G.A., Allmaras, R.R. and Johnson, C.E. 1983. Grain-drill opener effects on wheat emergence. *Trans. ASAE* 27: 651-655, 660.
- Winter, J.P., Voroney, R.P. and Ainsworth, D.A. 1990. Soil microarthropods in long-term no-tillage and conventional tillage corn production. *Can. J. Soil Sci.* 70: 641-653.
- Withers, N.J. and Pringle, R.M. 1981. An investigation of wheat response to plant density and nitrogen application in the Manawatu/Rangitikei. *Proc. Agron. Soc. N.Z.* 11: 17-22.
- Witt, W.W. 1984. Response of weeds and herbicides under no-tillage conditions. pp. 152-170. (In) Phillips, R.E. and Phillips, S.H. (eds.), *No-Tillage Agriculture - Principles and Practices*. Van Nostrand Reinhold Company, New York, N.Y., U.S.A.
- Wittmuss, H.D., Olson, L. and Lane, D. 1975. Energy requirements for conventional versus minimum tillage. *J. Soil Water Conserv.* 30: 72-75.
- Wolf, D.D. and Edmiston, K.L. 1989. Late season alfalfa plantings: conventional vs. no-till methods. *Crop Sci.* 29: 170-175.
- Zhai, R., Kachanoski, R.G. and Voroney, R.P. 1990. Tillage effects on the spatial and temporal variations of soil water. *Soil Sci. Soc. Amer. J.* 54: 186-192.

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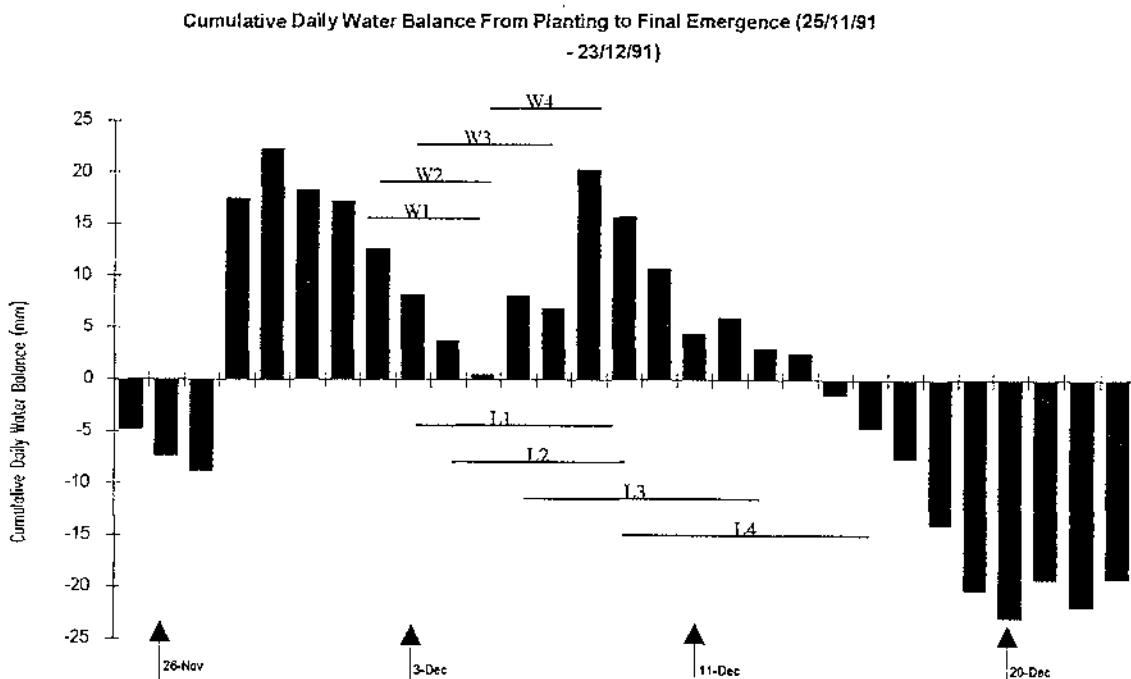
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8. APPENDICES

Appendix 1. Soil and environmental data

1.1 Relative cumulative daily water balance, illustrating wetting and drying cycles experienced by seeds and seedlings from the time of planting (25/11/91) until final emergence (23/12/91). All figures are relative to moisture levels at the start of the experiment, which was arbitrarily assigned a zero value. These water balance figures were calculated from daily rainfall and pan evaporation readings from a weather station, operated by AgResearch, situated about 1km from the trial site.



N.B. (i) The dates noted by the arrows in the graph above refer to the sampling dates for soil moisture. These are presented in the table (1.2) on the following page.

(ii) The horizontal bars represent the spread of emergence between 5% and 95% of those seeds which emerged. W = wheat; L = lupin; 1 = D1 (20mm); 2 = D2 (30mm); 3 = D3 (50mm); 4 = D4 (70mm).

1.2 Table of gravimetric soil water contents at different depths, sampled at four separate times during germination and emergence.

Soil Depth (mm)	Soil Moisture (% w/w)			
	<u>26/11/91</u>	<u>3/12/91</u>	<u>11/12/91</u>	<u>20/12/91</u>
0 - 20	20.2 a§	27.4 a	24.4 a	19.5 a
20 - 40	22.8 b	26.8 a	26.1 ab	22.5 b
40 - 60	23.8 bc	26.9 a	26.5 b	23.6 bc
60 - 80	24.8 c	26.8 a	27.2 b	24.7 c

§ - Numbers within a column followed by the same letter are not significantly different ($P \leq 0.05$).

1.3 Soil moisture calibration for Turitea silt loam, adapted from Pellow (1992). Nearly identical results could be expected for the silt loam soil used in this experiment, particularly in the top 100mm (A. Palmer, pers. comm., 1992).

Soil Water Tension (kPa)	5	10	50	100	200	300	600
Soil Water Content (% w/w)	62.5	52.9	31.3	25.2	21.0	19.8	18.6

1.4 Daily temperatures (air maximum, grass minimum and soil at 100mm depth) from planting (25/11/91) until final emergence (23/12/91). These readings were obtained from a weather station, operated by AgResearch, situated about 1km from the trial site.

