



**PROJECT REPORT No. OS31**

**ESTABLISHMENT OF OILSEED  
RAPE: THE INFLUENCE AND  
PHYSICAL CHARACTERISTICS  
OF SEEDBEDS AND WEATHER  
ON GERMINATION,  
EMERGENCE AND SEEDLING  
SURVIVAL**

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GERMINATION, EMERGENCE AND SEEDLING SURVIVAL**

by

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## SUMMARY

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Oilseed rape is the third largest combinable crop in the UK. In 1996/97, 430,000ha were cropped with oilseed rape with an estimated 90:10 split between autumn and spring sowings (MAFF statistics) due primarily to the larger yields from autumn sowings. As in any arable cropping system, the establishment period is crucial. Too few plants will restrict canopy expansion during autumn, reducing growth and the ability of the crop to compete with weeds and recover from pigeon grazing. Patchiness in crops exacerbates the problem by reducing the uniformity of crop growth and development leading to less uniform ripening, often necessitating the greater use of pre-harvest desiccants. In extreme cases, total crop failure requires crops to be resown or the cropping sequence to be changed. Winter rape crops are at risk to plant loss during a six month period from September to February, and in the worst years, establishment can be so poor that up to 30% of rape crops have been abandoned. Plant failure during establishment is usually associated with poor seedbeds: almost three quarters of the oilseed rape grown is drilled into clay soils and it is on these soils, especially where cereal residues have to be incorporated, that seedbed preparation is difficult and crop failure most likely to occur.

From autumn through winter into early spring, many factors can operate to reduce plant populations, and a key part of ascribing 'cause and effect' is to determine precisely when plants are lost and relate this to the seedbed characteristics, weather and biotic pressures operating during that phase. This report examines the detailed relationships between the physical characteristics of the seedbed, the interactions with the weather and the performance of the seeds and seedlings in the absence of pests and weeds.

A previous study by McWilliam, Stokes, Scott, Norton, Sylvester-Bradley and Davies (1995)(HGCA Project report OS13) examined the effect of cultivation equipment on seedbed production in the presence of cereals residues and on subsequent seedling survival. This analysis clarified the effects of cultivation equipment on seedbed structure, identifying that a seedbed could be grouped into one of three broad categories: uncultivated (e.g. direct drilled), mixed (e.g. disced) and inverted (e.g. ploughed) and that the effects on the seed and seedling were largely the result of the structure of the seedbed and were not strictly linked to the type of implement used. Furthermore, this work showed conclusively that it was necessary to identify precisely when plant losses occurred so they could be related to the specific factor (or combination of factors) operating at the time of loss. The work reported here, builds on these

initial investigations by providing more detailed information about the relationship between the individual physical factors operating within a range of seedbeds.

A series of experiments were conducted in both controlled environments and small scale field sowings at the University of Nottingham. The main findings from this work are reported below.

Germination was progressively restricted as soil moistures fell below critical levels. The 'availability' of water in a soil can be measured in terms of the pressure required to 'pull' water from the soil surface (water potential). Water potentials greater than -1.5 MPa severely restricted germination. The precise soil moisture at which germination was restricted was specific to an individual soil type because different proportions of clay, sand and silt modify the availability of water in the soil. For example, a sandy loam with 10% clay particles had to be dried to 5% moisture before seeds could not draw water, whereas in a clay soil with 50% clay particles, this point was reached at a moisture content of 23%. These results demonstrate the importance of understanding the water release characteristics of soils when determining the amount of rainfall required to raise exceptionally dry soils to water contents where water release will be sufficient to get most seeds through the germination and emergence stage. Furthermore, as seedbeds dried and approached the limiting deficit of -1.5 MPa, there was a progressive decline in germination not a sudden cut-off. Thus at the scale of the seed, some niches of the seedbed were 'wetter' than others or seed/soil contact was greater.

Laboratory investigations showed that during the early stages of germination when seeds were taking in water (imbibing), severe desiccation before radicle (root) protrusion did not kill the seed and once water was again available, germination proceeded. However, if drying occurred after the radicle had protruded through the seed coat, the seeds were usually killed. Short term desiccation often did not kill the seed directly, but resulted in abnormal roots with fewer root hairs, thus impairing subsequent growth of the tap root rendering the plant vulnerable to further desiccation events.

In situations where soils are likely to dry rapidly, consolidation with a roll is common practice. Whilst soil drying is reduced and seed soil contact is increased, it is important not to over consolidate. Seedling emergence was shown to be very sensitive to compaction especially on clay soils: emergence from 2cm in an alluvial clay was significantly ( $P < 0.001$ ) poorer at bulk densities heavier than  $1.1 \text{ g cm}^{-3}$ . At a limiting bulk density of  $1.2 \text{ g cm}^{-3}$ , selecting large seed  $> 2\text{mm}$  in diameter increased the number of seedlings which emerged.

In laboratory investigations, seed sown deeper than 5cm in sand usually failed to emerge. In a clay soil, this 'critical' depth is less because of the greater resistance to emerging seedlings exerted by adhesion between clay particles. It was concluded that sowing depths between 2-3cm

provided the best compromise between the risk of desiccation and losses resulting from failure to emerge from depth, especially when a large proportion of the seeds is less than 2mm in diameter.

In the field, 19 sequential sowings between October 1993 and May 1995 produced a wide range of seedbeds and variations in weather during each of the stages of establishment: sowing to germination, germination to emergence and emergence to final establishment when plants would contribute to yield. Detailed measurements of germination, emergence and subsequent plant loss allowed the losses in each phase to be quantified.

Germination in the field, under normal autumn temperatures where water supply was unrestricted, was above 95% i.e. comparable to germination in the laboratory. Poor germination did result from drilling into cold wet soils and where soil temperatures were below 3°C germination fell to 70%. Although such conditions are unlikely following drilling at more normal time this finding does indicate that there are important weaknesses in some seedlots which need to be investigated further.

There was a strong relationship between accumulated soil temperature (at 2cm depth) and the thermal time between sowing and 50% emergence. In most situations, 160°C d were required for 50% emergence. In autumn field experiments, between 30 and 40% of seeds sown failed to emerge. Much of this was attributed to deep sowing with many seeds sown below 5cm; incorporation of cereal residues in the surface 10cm layer of the seedbed reduced average drilling depths by reducing drill penetration. Straw in the top 10cm of the seedbed acted as a mulch and increased the soil moisture content relative to seedbeds where the straw had been buried at depth or removed prior to cultivation. This additional moisture was beneficial during germination and emergence in dry conditions but exacerbated the effects of wet conditions over winter. The effect of aggregate size on germination and emergence were smaller than initially thought. Experiments and observations from the field where water supply was not limiting, suggest that as long as seedbeds do not contain large, platy aggregates which physically impede emergence or have loosely packed aggregates which result in excessive drilling depths, then germination and emergence are unlikely to be restricted. However, cloddy, loosely packed seedbeds dry more rapidly than fine consolidated seedbeds and hence consideration must be given to water supply to the germinating seed and emerging seedling where soil moisture is marginal.

In the absence of effects of pigeons and slugs, post emergence losses from September and October sowings on a non-calcareous alluvial clay were 30%, but on a lighter sandy loam only 11% of plants were lost. In both cases, the main losses were associated with freezing

conditions; in the case of the heavier, less well drained clay, these were exacerbated by waterlogging.

This report shows that the main phases during which losses occur are emergence and during frost conditions post emergence. More importantly, the key parameters responsible for these losses have been quantified, namely water supply, resistance to emergence and sowing depth during emergence and in post emergence losses time of sowing and drainage were critical factors. Surprisingly, straw and large aggregates were not deleterious to establishment as initially expected.

Combining this analysis with the previous studies of cultivation equipment suggests that the physical condition of the seedbed can be optimised for a given set of conditions by using appropriate cultivation equipment to exploit the natural tilth if present. These have been summarised in guidelines (Bullard, Heath, Clare, McWilliam, Stokes, Scott and Davies, 1996). In addition improved seed quality (e.g. seeds with greater vigour or more reserves - large seed) is likely to improve germination and emergence where conditions are not ideal e.g. cold seedbeds, compact soils, surface crusting and deep sowing.

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## 1. INTRODUCTION

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Oilseed rape is the third largest combinable crop in the UK. In 1996/97 430,000ha were cropped with oilseed rape with an estimated 90:10 split between autumn and spring sowings. Poor establishment from autumn sowings is a major problem resulting in very thin stands, patchy crops and in some cases complete failure. The majority of poor establishment is associated with clay soils, which accounts for 70% of the cropping area. Producing a satisfactory seedbed on these soils after cereals is often constrained by the weather, the original structure of the soil and/or the presence of cereal residues.

The establishment of autumn sown rape covers the seven month period normally between sowing in September through to stem extension in March. The final plant populations are influenced over this lengthy period by the complex interactions between, seedbed structure, weather, pests, diseases and weeds. The background to these interactions has been reviewed by Bullard, Heath, Clare, McWilliam, Stokes, Scott and Davies (1996) (HGCA Review OS10).

Prior to 1992, stubble burning was used as a quick and effective method of seedbed preparation, the exposed soil often required little or no further cultivation prior to drilling. However, environmental and safety concerns led to a ban on burning in England and Wales in 1992. The industry sought a derogation to allow cereal residues to be burnt where oilseed rape was to follow but this was rejected. Attention was therefore focused on developing cultivations and drilling strategies to ameliorate the effects of cereal residues.

A previous study by McWilliam, Stokes, Scott, Norton, Sylvester-Bradley and Davies (1995) [HGCA Project report OS13] examined the effect of cultivation equipment in the presence of cereals residues on seedbed production and subsequent plant survival. This helped clarify the effects of implements on seedbed production and identified three major seedbed types with respect to establishment: uncultivated (e.g. direct drilled), mixed (e.g. disced) and inverted (e.g. ploughed). It also identified likely effects of the soil physical characteristics (including straw) on germination, emergence and survival post emergence. However, because many factors operated in combination and interacted with pests, it was not possible to determine their individual effects.

To reduce the risk of poor establishment, the effect of individual characteristics need to be quantified and the interaction with weather conditions examined. This approach will identify those characteristics most likely to cause failure so that cultivation choice can be tailored to the prevailing conditions.

The objective of this project was to identify, in the absence of pests, diseases or weeds, the extent to which success or failure in establishment could be attributed to specific physical characteristics of the seedbed. The experimental programmes comprised of two main parts:

1. controlled environment studies with a small field experiment to quantify physical limitations to oilseed rape establishment: the experiments tested the effects of water availability, compaction, aggregate size distribution and depth of sowing on germination and emergence.
2. a major field study to examine the effect of weather on the establishment process. Sequential sowings between October 1993 and May 1995 compared up to three seedbed types, on two contrasting soils and tested the interaction between the physical characteristics of the seedbed and weather over a wide range of conditions.

For clarity, the elements of the experimental programme are reported separately. First, a review of the relevant literature is presented. Second, the effects of single influences (and some combined) on establishment are reported - because of their diverse nature, each experiment is reported separately with appropriate sections for introduction, materials and methods, results and discussion. Third, the sequential field sowings are reported to extend these investigations to the field where establishment occurred over a very wide range of conditions. Finally, the elements of the work are summarised in a discussion section.

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## 2. LITERATURE REVIEW

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Crop establishment is affected by physical, mechanical, chemical and biotic factors. These include water supply, temperature, oxygen, soil texture, depth of sowing, crusting of soil surface, soil structure, seed/soil contact, herbicide residues, soil pH, fertilisers, pests, diseases, weeds and crop residues, all of which may act singularly or in combination (Khan, Karssen, Leue & Roe, 1979).

The following sections define establishment and its measurement, consider the influence of seedbed structure in relation to soil texture, stability and cultivation, describe the main physical and chemical attributes of the seedbed environment which affect seed and seedling survival, the effect of weather on overwinter survival and finally considers biotic factors (pests, diseases and weeds) likely to influence oilseed rape establishment. Although this report focuses primarily on the effect of physical characteristics of seedbeds, chemical and biotic factors are included in this review since these inevitably interact under field conditions.

### 2.1 DEFINING AND MEASURING ESTABLISHMENT

An established seedling is one that 'is sufficiently intact to have the expectation of reaching maturity (Bradbeer, 1988). This definition encompasses, germination, emergence and post emergence growth. **Germination** describes the process by which a quiescent seed initiates the formation of a seedling from the embryo (Mayer & Poljakoff-Mayber, 1989). It commences with the onset of metabolic activity, which precedes visible growth of the embryo and the protrusion of the radicle and plumule through the seed coat. The precise transition from germination to emergence is contested; however, the protrusion of the radicle is generally recognised to mark the completion of germination (Mayer & Poljakoff-Mayber, 1989). **Emergence** describes the post germination growth and development of the seedling to the point at which it becomes autotrophic. In the context of epigeal field crops such as oilseed rape, this is associated with the appearance of the expanded cotyledons above ground level (Harper, 1983). The **Post emergence** phase encompasses the period from cotyledon expansion up to final 'establishment'.

In field investigations of autumn sown rape crops, the normal measure of establishment is the number of surviving plants, either in late autumn or in spring. In a study of cultivation effects on oilseed rape, Darby & Yeomans (1994) measured plant survival in autumn and in spring to distinguish between losses pre and post winter.

No reported studies on oilseed rape have examined the timing of losses by monitoring plant populations from first emergence through to final spring plant populations nor those losses which occur during emergence or as a result of germination failure.

## 2.2 SEEDBED STRUCTURE

### 2.2.1 Soil texture and stability

Low plant populations and patchy establishment are most commonly associated with 'heavy' soils where the clay content is greater than 35% because of the difficulties associated with cultivation and hence seedbed preparation. These soils comprise over half the area in Eastern England, the East Midlands and Eastern Scotland where oilseed rape production is most concentrated (Bullard, Heath, Clare, McWilliam, Stokes, Scott & Davies, 1996).

Clay soils differ in their behaviour due to the parent clay mineral (of which there are seven types), and by the relative proportions of silt and sand as well as the humified organic matter content (Fitzpatrick, 1983; Davies & Payne, 1988). The parent clay material alters the cation exchange capacity (CEC) and water retention of the soil. The CEC is important since it dictates the structural stability of the soil (Dexter, 1991). Most notably, the presence of calcium ions improves structure by creating chemical bonds between the clay micelles, supplementing the weak hydrogen bonds and promoting flocculation (binding) of clay particles to form stable aggregates. The various parent clay types and the presence or absence of calcium ions can be summarised into two agronomically important categories: *well structured calcareous* or *poorly structured non-calcareous* (Davies, B.D. personal communication). Typical examples of clay soils and their associated soil series are shown in Table 2.1. Overall, the poorly structured soils account for 72% of the area on which rape is grown, Table 2.2 shows the regional distribution of these two classes of soil in England and Wales.

The distinction between these two types is important because it effects the aggregate stability. In most undisturbed soils with high clay content, fine tilth develops at the surface due to wetting and drying cycles; however, in non-calcareous soils this beneficial tilth is prone to disaggregation due to the impact of rain droplets or compaction by farm machinery (Davies & Payne, 1988). The same is true of aggregates created by cultivation and in poorly structured non-calcareous soils seedbeds are more prone to slumping.

Table 2.1: Typical examples of clay soils subdivided according to their agronomically important properties with examples of the soil series with which they are associated. From Bullard *et al.* (1996).

Description	Soil Series where clays are present
<i>Poorly structured non-calcareous clays</i>	
Carboniferous shales	Hallsworth, Dale and Dunkeswick
London clay	Windsor and Hallsworth
Oxford clay	Denchworth
Keuper Marl	Worcester and Spetchley
Boulder clays	Ragdale, Crewe, Foggathorpe and Salop
Weald clays	Wickham, Dale and Denchworth
Alluvial clays	Compton, Fladbury and Midleney
Marine alluvial clays	Wallasea
<i>Well structured calcareous clays</i>	
Chalky Boulder clay	Hanslope and Stretham
Oxford clay	Evesham
Alluvial clay	Thames
Marine alluvial	Newchurch

Table 2.2: Relative proportions of non-calcareous and calcareous clays in England and Wales (by region). From Bullard *et al.* (1996).

Region	Poorly-structured non-calcareous clays		Well-structured calcareous clays	
	% of region	'000 ha	% of region	'000 ha
North	17.6	549	0.4	12
Midlands and West	15.3	422	2.7	75
East	16.6	455	16.2	444
South East	22.3	447	4.1	83
South West	12.7	305	6.8	163
Wales	2.3	47	0.4	7



### 2.2.2 Cultivation

The aim of cultivation, as far as soil structure is concerned, is to ameliorate the damage done by previous traffic or cultivations, to increase the permeability of the surface soil to water (thereby improving drainage and aeration) and expose fresh soil to beneficial weathering (Dexter, 1991). However, there is a danger that tillage may produce a temporary near perfect structure but which might be mechanically unstable and liable to collapse when wetted (Russell, 1973; Dexter, 1991). To be successful, cultivation must therefore produce a seedbed which meets the immediate requirements of the seed, but also provides for longer term growth.

The structure of cultivated seedbeds is determined by the initial soil structure and how the cultivation implement(s) alter that structure (Braunack & Dexter, 1989a, b). In order to understand how cultivations affect structure it is necessary to examine the forces exerted by different implements. These can be classified as one of three basic types: forward facing tine, vertical tine or backward facing tine (Davies, B.D. personal communication).

**Forward facing tines** lift and loosen soil but do not break clods. In general, they have a tendency to pull clods to the surface; the greater the depth of working, the larger the clod. They tend not to bury residues where present. The Mouldboard plough is a modified forward facing tine which inverts the soil and so effectively buries the existing surface aggregates and any crop residues. **Vertical tines** break clods but neither loosen nor compact. As with forward facing tines, little mixing of residues is achieved. Examples of vertical tine implements include the Dutch harrow and power harrow. **Backward facing tine** implements press down on clods to crush or cut them and consequently they have a tendency to consolidate and compact. An example of a backward facing tine implement is a rotary cultivator. Discs are a modified version since the concave disc confers a lifting and mixing action which is effective in incorporating residues. An extreme version of a backward facing tine is a roll.

The strength of aggregates will also affect the action of cultivation equipment. When clay soils are dry, the cation concentrations within the clay micelles are high, forming very strong bonds between particles and result in aggregates with high strength, often described as 'cemented'. Energy applied by cultivation serves to move existing aggregates rather than break them. As soil moisture increases, the soil becomes 'friable' and energy applied breaks the aggregates along planes of weakness which have developed through wetting and drying cycles, essentially accelerating the weathering process. When soil moisture increases to above the 'lower plastic limit' particle cohesion is weak and tillage implements tend to 'shear' aggregates apart leaving a smeared face along the plane of the applied force.

The precise ranges in moisture content over which a soil is *cemented*, *friable* and *plastic* are dependent on the textural properties and in the case of clays, the type of clay. Soils with high clay content have a much narrower moisture range over which they are friable than sandy soils and it is this characteristic which limits the creation of fine seedbeds in autumn.

### 2.2.3 The ideal seedbed structure

Soil structure refers to its aggregate size distribution and the shape and packing of the aggregates (Russel, 1973). The importance of seedbed structure for establishment of small seeded crops was summarised by Håkansson & Von Polgár (1984). They concluded that fine tilth at the soil surface and a well fissured underlying structure is favourable. A firm seedbed bottom helps control drilling depth and promotes water transfer to seed through capillary movement of water, the fine tilth improves seed soil contact and reduces evaporative losses while the well structured sub-zone provides good drainage and facilitates rapid root growth. In contrast, the platy structure associated with compacted surface tilth coupled with a poorly structured sub-zone presents few favourable characteristics.

Specific recommendations for oilseed rape state that the seed must be placed into a firm, moist, warm, aerated and well structured seedbed for rapid germination and seedling growth (Pouzet, 1995). However, the effects on establishment where these criteria are not, or cannot, be achieved are less clear and have not been adequately quantified.

## 2.3 EFFECTS OF THE SEEDBED ENVIRONMENT ON ESTABLISHMENT

### 2.3.1 Water supply

Prior to the formation of an extensive root system seedlings are vulnerable to desiccation. If transpiration exceeds water uptake for extended periods then plants become permanently wilted, a condition commonly associated with soil water availability of -1.5 MPa, when the soil is said to be at its permanent wilting point (Russel, 1973)

At the other extreme, waterlogging is not uncommon, especially on non-calcareous clays or soils with poor drainage resulting from structural damage. Waterlogging of oilseed rape at three development stages post emergence was investigated by Cannell & Belford (1980) using lysimeters; they found no effects from short term waterlogging (10 days) at growth stages 1,4 (fourth true leaf exposed), 1,5 (fifth true leaf exposed) or 4,1 (first flowers open) (Sylvester-Bradley & Makepeace, 1984). However, longer periods of waterlogging did induce effects; a 42 day waterlogging event starting at growth stage 1,4 with an average soil temp of 2.2°C over the

period resulted in reduced leaf expansion with characteristically purple colouration of leaves and shorter, thicker lateral roots. The same treatment imposed at growth stage 1,5 when soil and air temperatures were higher, had more dramatic effects; leaf area was reduced by 50%, dry weight by 40%, height by 25% and the seed yield by 14%. However, in neither case was plant fatality recorded.

### 2.3.2 Oxygen supply

The metabolic processes associated with germination require a supply of energy to sustain them. This energy is usually in the form of ATP produced through respiration, oxygen being the terminal electron acceptor in this pathway. Depletion of oxygen results in a switch to anaerobic respiration with the production of acetaldehyde, ethanol and lactate, all of which are potentially toxic to germinating seedlings (Bradbeer, 1988).

Water and air “compete” for the same free space in the soil profile. If the amount of water present in a soil is elevated above field capacity, the inter pore space becomes filled with water and the soil becomes saturated. In this state, there are no pockets of air within the soil and the seedbed becomes anaerobic (Brady & Weil, 1996).

A restricted supply of oxygen can also result from impedance of oxygen diffusion between the soil and the atmosphere (Hegarty, 1984) and competition for oxygen from fungi colonising the seed reported in barley (Harper & Lynch, 1981).

### 2.3.3 Temperature

Soil temperature is the main factor controlling germination of oilseed rape once seeds have imbibed water (Mendham & Salisbury, 1995).

The range and optimal temperature for germination of seeds is species dependent, some examples are given in Table 2.3. However, the precise temperatures differ both between varieties and within seedlots.

Table 2.3: Minimum, maximum and optimum germination temperatures for some common crop species.

(From Mayer & Poljakoff-Mayber, 1989 p55).

Species	Temperature (°C)		
	Minimum	Maximum	Optimum
<i>Triticum sativum</i>	3-5	30-43	15-31
<i>Hordeum sativum</i>	3-5	30-40	19-27
<i>Zea mays</i>	8-10	40-44	32-35
<i>Avena sativa</i>	3-5	30-40	25-31

Minimum and Maximum values for *Brassica napus* L. are not widely reported in the literature, but Wilson, Jensen & Fernandez (1992) found that germination in two cultivars was reduced at 2°C and at 40°C and above, however, within the range 5 - 35°C overall germination percentage remained the same. This was consistent with the work of Witcombe & Whittington (1971) who found no difference in total germination of spring cultivars between 5 - 25°C and with Kondra, Campbell & King (1983) who reported similar overall germination in both spring and winter cultivars between 2 - 25°C. In a study of two double low UK cultivars over the temperature range 4.8 - 24°C overall germination was observed to fall slightly at the lowest temperature with a calculated minimum base temperature of 3°C (Marshall & Squire, 1996).

The rate of germination has been shown to increase as temperatures rise (between 2 and 35°C). Kondra *et al.* (1983) found mean times to germination increased from 1 day at 21-25°C to 11-14 days at 2°C.

Combining both the minimum temperature requirement with the rates of germination allows the thermal time (the number of temperature units accumulated over a time period above a base level) to be determined. This is commonly expressed as growing degree hours (GDH) or degree days (°C d), both above a base temperature. In relation to developmental processes under field conditions, degree days are more relevant.

The thermal times for emergence under field conditions have been reported in limited studies; Leterme (1988) showed that 130 - 140°C d (above zero) were required in a winter cultivar, while in a Canadian study on the spring cultivar Westar 98 °C d (above zero) were required (Morrison, McVetty & Shaykewich, 1989).

#### **2.3.4 Cereal residues**

Cereal residues concentrated in the upper horizons of the seedbed have been associated with poor establishment in both cereals and oilseed. In a study on winter wheat establishment on a calcareous clay soil (Denchworth series), drilling direct through chopped straw or conventional drilling after shallow incorporation of straw by tines to 5cm resulted in significantly fewer plants establishing and lower seed yields compared with similar cultivations following the burning of straw (Christian & Bacon, 1991).

Prior to 1992, most cereal residues were burnt. This provided rapid and economic removal of all cereal residues, reduced damage to soil structure through trafficking by baling and bale removal, improved aggregate stability, lowered the risk of phytotoxic metabolites from decomposing straw, reduced slug populations, lessened disease by removing the "green bridge" and killed volunteer cereal and weed seeds (Ellis, 1979; Lynch & Elliot, 1984).

However, in 1992, EU legislation banned the burning of cereal residues in England and Wales on the basis of environmental damage, despite the potential adverse effect of cereal residues on establishment.

Straw physically interferes with drilling by blocking drill coulters and preventing drill penetration, culminating in poor seed placement (Lynch & Elliot, 1984; Naylor, Marshall & Matthews, 1983). Direct drilling through surface trash can result in cereal residues being pressed into the bottom of the drill slit (Ellis, Christian & Cannell, 1982; Ellis & Lynch, 1979) which reduces seed soil contact, impeding moisture uptake and subsequent germination (Harper & Lynch, 1981).

Cereal residues are also reported to have allelopathic effects on the subsequent crop. Phytotoxic compounds released from decomposing crop residues have been widely reported (Elliot, McCalla & Waiss, 1979; Lynch & Gunn, 1978; Wallace & Elliot, 1979) and have been linked to poor establishment in wheat, barley, cotton grass and oilseed rape under field conditions (Scott, 1975; Habeshaw, 1980). Phytotoxicity is most commonly associated with anaerobic decomposition (Ellis & Lynch, 1979; Wallace & Elliot, 1979) and the associated production of acetic, butyric and propionic acids which have been implicated as the main causal agents of seedling failure (Lynch, 1977). Figure 2.1 shows the aerobic and anaerobic decomposition pathways.

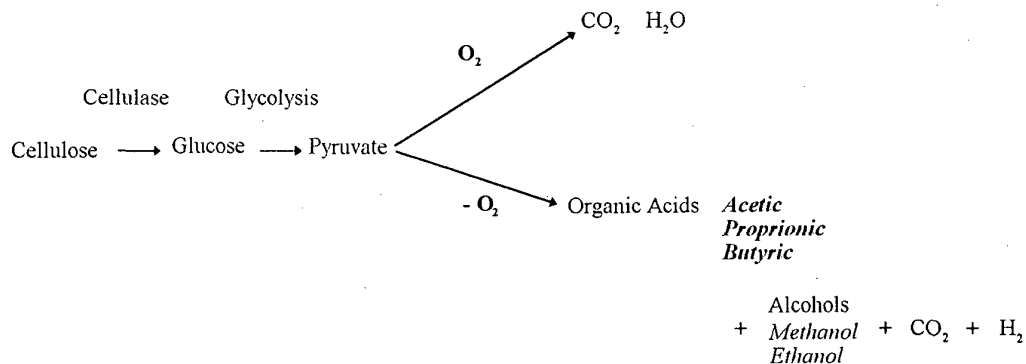


Figure 2.1: The breakdown of cellulose under aerobic and anaerobic conditions. Adapted from Wolfe (1971).

Under laboratory conditions, Lynch (1977) demonstrated that extracts from the anaerobic decomposition of wheat inhibited elongation of barley roots by 25%, while the products of the aerobic decomposition increased root elongation by 25%. In a related experiment, the fermented extract from wheat straw containing 17 mM acetic, 0.8 mM propionic and 0.3 mM butyric acid reduced root extension of *Brassica napus* by 47%, (Lynch, 1977). Only the concentration of acetic acid was considered high enough to account for the inhibition, although propionic and butyric acid are 2 and 3 times as phytotoxic at equivalent concentrations.

However, the relevance of organic acids under field conditions is questionable. Lynch, Gunn & Panting (1980) showed that in a silt loam (Hamble series) at its maximum water holding capacity, the decline in acetic acid concentration with distance from wheat or barley straw was exponential; a 50% reduction in the concentration of acetic acid at the straw surface occurred within 1.5 cm in barley and 1.7 cm in wheat straw. This suggests that to have an inhibiting effect, straw would have to be in close contact with the seedling. This is consistent with the observations of Hicks, Wendt, Gramaway & Baker (1989) who reported that under field conditions, germination and emergence of cotton seeds was only inhibited when the seeds were in direct contact with straw

The decomposition of straw can also affect crop establishment since it immobilises nitrogen that would otherwise be available for plant growth (Russel, 1973). This occurs because straw has a high C:N ratio which results in uptake of N by the fungi and bacteria to create organic nitrogen compounds (Jensen, 1929, cited by Russel, 1973). Pinck, Allison & Gaddy (1946) found that 1 tonne of wheat straw immobilised about 8 kg of nitrogen when decomposing during the winter. The immobilisation of nitrogen has implications for autumn crop growth because nitrogen is an essential constituent of all plant proteins and nucleic acids (Wild, 1988). Leaf initiation has been shown to increase with additional seedbed N (Scott, Ogunremi, Ivins & Mendham, 1973a; Menham, Shipway & Scott, 1981a) as has overall plant growth and dry matter accumulation during autumn.

### **2.3.5 Nutrient requirements**

A full review of the nutritional requirements for growth is beyond the scope of this report, but has been comprehensively reviewed by Holmes (1980) and Chalmers, Darby, Evans, Sinclair & Withers (1992). The major consideration for establishment from autumn drilling is nitrogen availability as this is a key determinant of autumn growth and hence crop size over winter.

## 2.4 EFFECTS OF WEATHER ON ESTABLISHMENT

### 2.4.1 Winter kill and frost heave

Winter kill describes plant losses resulting from freezing temperatures over the winter period (Harper, 1983). The extent of freezing injury depends on the duration of the frost, and its effects may be immediate or slow and indirect (Weiser, Quamme, Proebsting, Burke & Yelenosky, 1979 cited by Anon, 1992). Westwood (1978) affirmed that it was not low temperatures that kill plants but ice formation.

Two types of freezing in plants are recognised: extracellular freezing and intracellular freezing (Saki & Larcher, 1987). Slow temperature changes often cause extracellular freezing while intracellular freezing is more likely when temperatures fall rapidly (Westwood, 1978). Intracellular freezing is immediately fatal resulting in mechanical destruction and disruption of the cytoplasm and denaturation of proteins. Extracellular freezing sets up a water potential gradient which drives water out from the cell protoplast into the intercellular space. This may or may not cause injury depending on the speed and extent of the dehydration process (Weiser *et al.* 1979).

Rape is considered frost hardy since it can tolerate ice in its tissue (Single & Marcellos, 1981) and has a nominal tolerance as low as  $-5^{\circ}\text{C}$  (Kacperska-Palacz, 1978). However, cold tolerance is dependent on assimilate reserves and the rate of the reduction in temperature (Kacperska-Palacz 1978). A gradual reduction in temperature triggers metabolic changes which convert starch reserves to sugars (Kacperska-Palacz, Blaziak & Wcislinska, 1969; Kacperska-Palacz & Wcislinska, 1972) and results in the accumulation of water soluble proteins (Kacperska-Palacz, Dlugokecka, Breintenwald & Wcislinska, 1977; Kacperska-Palacz & Wcislinska, 1972) both of which confer greater cold tolerance. The developmental and growth stage for maximum winter hardiness has been determined as when the stem base is 5-16 mm in diameter and stem elongation is less than 30 mm (Topinka, Downey & Rakow, 1991).

Plants are also killed by frost heave. The precise mechanism is still not fully understood but was summarised by Miller (1980). As soil temperatures drop to below  $0^{\circ}\text{C}$  single ice crystals are nucleated (initiated). These discrete ice units develop into an ice lens which grows as water adjacent to the ice lens itself becomes frozen. The accumulation of ice exerts pressure and brings about heaving. An ice lens at the soil surface that forms around a seedling will exert an upward pressure on the seedling. The growth of the ice lens effectively pulls the seedling out of the ground and may also cause the stem to snap; in either case the seedling is likely to

desiccate. Ice lenses further down the profile result in layers of soil being levered apart which snaps stems and roots that were contiguous between each layer.

Heaving is dependent on water supply to the ice lens and consequently soil texture and structure influence the extent of frost heave. Saturated soils are more susceptible as are those soils with a good structure which facilitates water movement. In general, Hayhoe and Balchin (1990) concluded that tillage or disturbance of soil increased the susceptibility to heave.

## **2.5 EFFECTS OF BIOTIC FACTORS ON ESTABLISHMENT**

### **2.5.1 Pests**

A detailed review of the effect of pests is beyond the scope of this report, however, an understanding of their potential impact is relevant to field trials and is therefore a brief summary is included as background.

#### *2.5.1.1 Slugs*

Grey field slugs (*Deroceras reticulum*) are a major pest problem on wheat and oilseed rape (Glen, 1989; Glen, Jones & Fieldsend, 1990). Damage to wheat results from hollowing out of seeds, eating through shoots during emergence and shredding of seedling leaves (Glen, Spaul, Mowat, Green & Jackson, 1993). It is not known whether slugs feed on seeds and emerging seedlings of oilseed rape (Glen, D. personal communication) but characteristic leaf shredding on young seedlings can be fatal (Glen *et al.* 1990).

Slugs are most common on heavy soils and depend on moist conditions for activity and survival (Glen, 1989). In general fewer slugs are found where straw is burnt as opposed to incorporated (Glen, 1989). However, cultivation can reduce slug populations by mechanical action or by drying the soil (Glen, Wiltshire & Milsom, 1989). Slugs traverse through the soil by following natural fissures and therefore unconsolidated, cobbly seedbeds promote rapid movement as do open drill slits left after direct drilling.

In studies on winter wheat, seedling damage was directly related to the biomass of slugs and inversely related to depth of sowing and the percentage of aggregates less than 6.1 mm in the upper soil profile (Glen *et al.* 1989) but no studies have been conducted on oilseed rape.

Slug populations have increased over recent years due to set-aside which offers an undisturbed site and the presence of cereal residues which provide a more consistent food source and moist environment.



### 2.5.1.2 Pigeons

Wood pigeons (*Columba polumbus*) are a major pest on oilseed rape, feeding on young seedlings and plants between late autumn and early spring, stripping them of foliage and in extreme cases removing the growing tip (Inglis, Thearle & Isaacson, 1989). Pigeons prefer landing on bare ground with clean footing and grazing therefore tends to progress outward from loci of poorly established patches. The size of patches is increased because loss of foliage before and during winter reduces overwinter survival of the rape plants.

### 2.5.2 Diseases

Damping-off diseases and seedling rots can be caused by *Alternaria spp.*, *Fusarium spp.*, *Pythium spp.*, *Phoma lingam* and *Rhizoctonia solani*. Infection risk is greater under warm, damp conditions especially where oxygen supply is restricted.

Plants are most affected after emergence by three main diseases over the autumn / winter period:

1. downy mildew (*Peronospora parasitica*)
2. phoma canker (*Leptosphaeria maculans*)
3. light leaf spot (*Pyrenopeziza brassicae*)

Susceptibility is dependent on climatic conditions and soil conditions, presence of crop residues, rotational position and varietal susceptibility.

Downy mildew is a seed and soil borne pathogen present on the majority of rape crops. The disease results in leaf necrosis, but seedlings normally grow and develop at a faster rate than the disease. However, late sown crops can be killed, particularly where infection occurs in combination with frost damage (Smith & Margot, 1987).

Phoma leaf spot is observed from October onwards. Infection risk is increased by proximity to rape stubbles and high rainfall between July and September (Gladders & Musa, 1980). Significant infection can result in impaired growth and lead to stem canker. In some cases, this can develop in autumn (as in 1993) and lead to winter losses.

Light leaf spot is usually observed between October and December. Infection risk is related to the incidence of pod disease in the previous oilseed crop. Severe infection can result in 50% crop loss over winter.

### 2.5.3 Weeds

Oilseed rape is a strong competitor with weeds (Ward, Basford, Hawkins & Holliday, 1985). However, this competitiveness is conferred by rapid stem extension in spring and before this stage the young plant is susceptible to competition for moisture, nutrients and light, especially where pigeons, slugs or disease have weakened growth.

Lutman, Bowerman, Palmer & Whytock (1995) ranked a range of weeds in order of competitiveness with oilseed rape and found *Galium aparine*, *Papaver rhoeas*, *Stellaria media* and *Sinapis arvensis* to be most competitive. Volunteer cereals also present a serious threat to establishment, especially if the oilseed rape plant population is low and/or is late sown (Lutman, 1991).

## 2.6 SUMMARY

It is clear that many factors, physical, chemical and biotic can operate to affect establishment. However, comparatively little data has been published specifically on oilseed rape with few references to the physical aspects of seedbeds. Only with these data can a greater understanding of the factors which dictate establishment of oilseed rape be gained and better guidance given to growers on which features of the seedbed are most critical.

The first step in this investigation was to identify candidate factors, related to the physical structure of the seedbed, which have the greatest potential influence on oilseed rape establishment. This was addressed by measuring seedbed characteristics in cultivation trials and assessing the magnitude of the effects during the establishment process (McWilliam *et al.* 1995 - HGCA project report OS13). Having identified these key factors, it is necessary to quantify their effect under controlled laboratory conditions without the confounding influence of biotic factors (Chapter 3) and finally under field conditions (but with minimal biotic interference) measure the combined effects of physical characteristics during the whole establishment phase over a range of weather conditions (Chapter 4).



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### 3. INVESTIGATIONS OF PHYSICAL LIMITATIONS TO GERMINATION AND EMERGENCE

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#### 3.1 INTRODUCTION

Cultivation experiments have identified that a large proportion of seeds or seedlings failed to produce emerged seedlings (McWilliam *et al.* 1995) [HGCA report OS13]. Although it was not possible to directly ascribe the physical characteristics of the seedbed which caused these losses, candidate factors were identified. The work reported in this section quantifies the effect of the main physical characteristics of seedbeds on seed germination and seedling emergence, in the absence of the confounding influence of biotic or weather factors.

#### 3.2 WATER AVAILABILITY IN RELATION TO SOIL TYPE

##### 3.2.1 Background

In dry years, a measure of gravimetric soil moisture content (%) is not a good indicator of the availability of water to the seed. For example, McWilliam *et al.* (1995) showed that on the Denchworth series with 32% clay, germination and emergence proceeded at soil moisture contents of 16% but on the heavier Evesham series soil with 52% clay, germination was delayed until the moisture content was above 21%. The explanation for this lies in the relationship between gravimetric water content and the water potential of the soil i.e. the tenacity with which the water is held by the soil in the interstices (pores) between the solid particles and by hydrogen bonding of water molecules onto clays (Brady & Weil, 1996).

The soil water potential ( $\psi$ ) is defined as the difference between the energy of soil water and that of pure water in a standard reference state (Brady & Weil, 1996). By convention, the water potential of pure water at atmospheric pressure, at a defined temperature, is zero (Green, Stout and Taylor, 1984) and thus water potentials are always negative. The unit of measure in biological systems is pressure, SI unit Mega Pascals (MPa), although much of the quoted literature uses bars<sup>®</sup>. Water movement between two areas is determined by the relative difference between water potentials such that water moves from an area of high potential to low water potentials (Brady & Weil, 1996).

Total water potential  $\psi$  is a measure of three component potentials: solute (osmotic) potential ( $\psi_s$ ), gravitational potential ( $\psi_g$ ) and matric potential ( $\psi_m$ ) (Equation 3.1). Each potential results from a different force and all three act simultaneously to influence water behaviour (Brady & Weil, 1996).

Equation 3.1: Water potential expressed as its component parts

$$\psi = \psi_s + \psi_g + \psi_m$$

Gravitational potential ( $\psi_g$ ) is determined by acceleration due to gravity and the height of the soil water above a reference elevation. This potential influences the downward movement of water and has a dominant role during downward drainage by saturated flow. The matric potential ( $\psi_m$ ) results from the adhesion (adsorption) of water onto soil particles and the cohesion of water molecules within the pores between soil particles (capillarity). The solute potential ( $\psi_s$ ) is attributable to the presence of solutes in the soil such as inorganic salts or organic compounds which “attract” the water molecules. Solute potential has little effect on the mass movement of water but is important in relation to water transfer between soil and seed/roots when solute concentrations are high; for example, when seedbed nitrogen is applied and soil moisture content is low.

When a soil is at its *maximum retentive capacity*, both the macropores (between aggregates) and the micropores (within aggregates) are water filled and its water potential is close to zero. In this state the soil is waterlogged and water moves by saturated flow through the macropores. Although water is freely available to plants, the anaerobic conditions are deleterious to both seed germination and seedling growth (Davies, Eagle & Finney, 1993). Drainage due to the hydraulic gradient causes the macropores to become air filled, but the micropores are still water filled; this occurs at water potentials of around -0.01 MPa and is termed *field capacity* (Brady & Weil, 1996). Water is readily available to plants at this potential since the water potential of the seed/roots are lower (more negative). As soil moisture decreases and the matric potential of the soil becomes more negative, the potential difference between the soil and the seed/roots decreases. At a water potential of -1.5 MPa most of the water is held in the micropores. This is termed the *permanent wilting point (PWP)* since most crop species are

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© 1 bar = 0.1 MPa

unable to extract water, through the roots, at water potentials below this level. The water held in a soil between field capacity and permanent wilting point is termed the *available water capacity* (AWC) (Brady & Weil, 1996).

The matric potential at a given soil moisture is influenced by the size of the pores between aggregates, the soil textural class and the organic matter content. The latter two have the greatest influence at low soil moistures. Clays have a greater surface area to unit volume ratio than silt so they can absorb more water and consequently will exhibit a higher moisture content for a given water potential; silt in turn, has a greater ratio than sand (Brady & Weil, 1996).

The relationship between the water potential and soil moisture content describes the water release characteristics of a soil and hence the available water content. A water release curve for a soil can be created by plotting the log of the pressure ( $\equiv \log \psi$ ) against soil water content for a range of pressures. The characterisation of soils through determination of relative proportions of clay, silt and sand and the use of water release curves to characterise soils is a procedure covered in all major soil science text (Brady & Weil, 1996; Russell, 1973; Fitzpatrick, 1986). It provides a quantitative measure of the soils and is therefore considered a pre-requisite to comparison of their behaviour in relation to the establishment process.

### 3.2.2 Objective

To determine the particle size distribution and the associated water release characteristic of the soils relevant to the experimental programme in order to interpret the effects of soil moisture content on water supply to the seed and seedling.

### 3.2.3 Materials and Methods

Soil samples were obtained from the top 5cm of the soil profile from the Drayton, Kneesall, Lidlington and Swineshead field sites used during previous cultivation experiments (McWilliam *et al.* 1995) and from two fields on the University of Nottingham Farm (Table 3.1); the latter were used in subsequent field experiments (Chapter 4). The soil series for each location were determined from soil maps (Ragg *et al.* 1984).

Particle size analysis was conducted by ADAS analytical laboratories using a pipette method (Anon, 1986). Six soil fractions were derived in the particle ranges 2000-600 $\mu\text{m}$  (coarse sand), 600-212 $\mu\text{m}$  (medium sand), 212-63 $\mu\text{m}$  (fine sand), 63-20 $\mu\text{m}$  (coarse silt), 20-2 $\mu\text{m}$  (fine silt) and <2 $\mu\text{m}$  (clay). The proportion of each fraction was calculated on a dry weight basis; the sub-fractions of sand and silt were combined to give an overall percentage by weight of clay, silt and sand. In addition, the organic matter content was determined for each sample.

Water release curves were prepared for each of the soils except the Denchworth soil from Swineshead because resources were limited. The specific objective of this experiment was to determine the release characteristics associated with the *particle size* distribution, as distinct from the effect of *aggregate size* on water holding capacity. In order to minimise the effect of aggregate packing, a soil fraction <2mm was prepared by sieving through a 2mm square mesh endecote sieve. To achieve sufficient quantities of this fraction, it was necessary to subject the Evesham, Denchworth and Fladbury soils to cycles of wetting and drying in combination with repeated rolling with a garden roll.

The gravimetric moisture content of three replicates of each soil was determined at water potentials of -0.0005, -0.001, -0.0025, -0.005 and -0.01 MPa using a sand table and at -0.02, -0.05, -0.1, -0.2, -0.5 and -1.5 MPa on a pressure plate apparatus.

The water release data were plotted as the log of the pressure head against gravimetric soil moisture (g/g) and a curve fitted using the Van Genuchten equation (Equation 3.2).

Equation 3.2: The Van Genuchten equation

$$W_E = \frac{W - WCR}{WCS - WCR} = \frac{1}{[1 + (\alpha h)^n]^m}$$

where:

$W_E$  = the effective water content

$W$  = water content after drying to constant weight

$WCS$  = saturated water content at  $\frac{dW}{dh} = 0$

$WCR$  = residual water content at  $\frac{dW}{dh} = 0$

$\alpha$  = empirical constant

$h$  = suction in mbar

$n$  = empirical constant

$m = 1 - \frac{1}{n}$

From Equation 3.2,  $W_E$  was calculated for  $h$  over a range of values and used to derive  $W$  (Equation 3.3). This equation accounted for over 95% of the variation for each soil ( $P < 0.05$ ).

Equation 3.3: Van Genuchten equation resolved for  $W$  (water content at suction  $h$ )

$$W = W_E(WCS - WCR) + WCR$$

### 3.2.4 Results and Discussion

The results of the particle size distribution and organic matter content are shown in Table 3.1. The textural class of the soil was determined from the proportions of clay, silt and sand

using the United States Department of Agriculture (USDA) triangular diagram of textural class (Fitzpatrick, 1983).

These data helped to explain a number of observations from the cultivation trials described by McWilliam *et al.* (1995). The high silt content of the Worcester soil at Kneesall explains two observations. First, the relatively high proportion of fine 'aggregates' measured on this soil in 1992 where the seedbed structure was 'massive' and unstructured, were probably silt particles from dispersed aggregates. Second, the 'slumping' of the surface aggregates on this soil, where irrigation was applied after ploughing, is typical of the unstable nature of silt soils (Davies & Payne, 1988; Davies *et al.* 1993). The fact that the unstable Denchworth series soil at Lidlington did not also exhibit structural collapse when irrigation was applied can be partly attributed to its relatively high organic matter content which confers stability (Davies *et al.* 1993).

Table 3.1: Particle size distribution and organic matter content of the soils used in the experimental programme.

Site	Grid Reference	Soil Series	Textural Class	Particle size distribution (%)		Organic matter (%)
Drayton	SP 158 553	Evesham calcareous	Clay	Clay	52	n/a
				Silt	28	
				Sand	14	
Kneesall	SK 698 643	Worcester non- calcareous	Silty Clay	Clay	30	2.84
				Silt	54	
				Sand	16	
Lidlington	SP 995 397	Denchworth non- calcareous	Clay loam	Clay	32	7.28
				Silt	30	
				Sand	38	
Swineshead	TL 065 667	Denchworth non- calcareous	Clay	Clay	43	3.30
				Silt	36	
				Sand	21	
University of Nottingham Field 8	SK 515 267	Fladbury non- calcareous	Clay	Clay	47	5.56
				Silt	32	
				Sand	19	
University of Nottingham Field 9	SK 512 266	Dunnington Heath	Sandy loam	Clay	14	2.65
				Silt	25	
				Sand	71	



The water release data show the strong association between particle size distribution and water availability; clay content in particular was strongly correlated such that soils with a greater clay content exhibited less available water at any given soil moisture (Figure 3.1). The curves produced in each case were typical for the soil particle distribution (Brady & Weil, 1996).

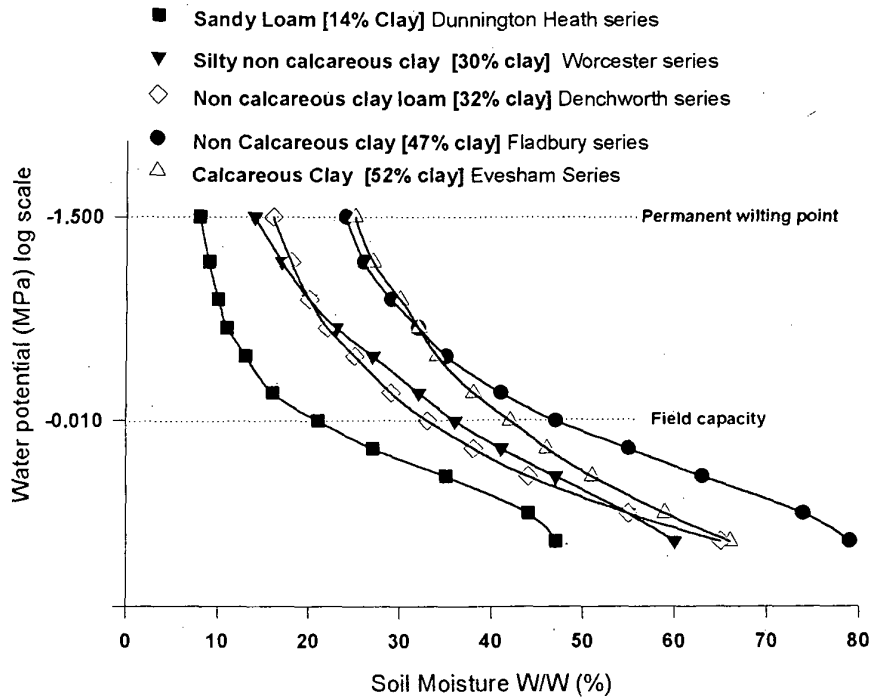


Figure 3.1: Soil water release curves for the five soils used in the experimental programme. Lines are fitted curves derived from the Van Genuchten equation.

The water release data help to explain why emergence was recorded in cultivation trials on the Denchworth series soil, but not on the Evesham series soil despite both having soil moisture contents of 21% (McWilliam *et al.* 1995). At this moisture content, the Denchworth series soil had a water potential equivalent to -1.0 MPa but on the Evesham series soil it was equivalent to -2.0 MPa. However, the exact water potential required for germination is not clear from these data nor is it reported by other researchers. This important criteria is investigated in Section 3.3. If the water potential requirement for germination was resolved it could be combined with the water release curves to identify the critical moisture content required for germination. This would be valuable as it would then be possible to determine from the gravimetric water content whether or not germination could proceed and if water content was marginal, this could influence cultivation choice e.g. avoid deep cultivations to conserve moisture.

### 3.3 THE RELATIONSHIP BETWEEN WATER POTENTIAL AND GERMINATION

#### 3.3.1 Background

Germination is dependent on adequate moisture supply; Hunter and Erikson (1952) demonstrated that in different species, seed moisture content by weight must be elevated above certain thresholds before germination will proceed e.g. maize 30.5%, rice 26.5%, soyabeans 50% and sugarbeet 31%. This has not been defined for oilseed rape.

Seeds imbibe water in liquid or gaseous form which causes swelling through its absorption by the protein, cellulose, pectin and mucilage fractions of the seed, as well as occupation of the free capillary spaces (Mayer and Poljakoff-Mayber, 1989). Imbibition is considered by many to be a special case of osmosis and consequently is sensitive to the concentration of solutes in the surrounding medium (Mayer and Poljakoff-Mayber, 1989), e.g. nitrates from fertilisers. However, the major factor limiting water transfer under field conditions is the matric potential (Collis-George and Sands, 1962).

The threshold water potential which will result in imbibition and subsequent germination is species dependent. This has been investigated by measuring germination in solutions with different water potentials created by manipulating  $\psi_s$  using different salt/sugar concentrations and more recently polyethylene glycol which regulates  $\psi_m$ . Hunter and Erikson (1952) reported threshold water potentials for maize (-1.3 MPa), rice (-0.8 MPa), soyabeans (-0.67 MPa) and sugar beet (-0.35 MPa). Williams & Shaykewich (1971) investigated water uptake, and germination in *Brassica napus* L. at matric potentials -0.06, -0.28, -0.78 and -1.5 MPa using pressure membrane apparatus. The reduction in water uptake with decreasing matric potential was small but both the rate and total germination was reduced with decreasing matric potential.

Using polyethylene glycol (PEG), Pekrun & Lutman (personal communication) determined the threshold water potential for four double low cultivars of *Brassica napus*. They showed that as the water potential was reduced from -0.2 MPa total germination declined and at -1.5 MPa less than 13% of seeds sown germinated (Table 3.2).

Table 3.2: Germination of four oilseed rape cultivars at different water potentials.

From Pekrun & Lutman (personal communication).

Cultivar	Water potential (MPa)				
	-0.2	-0.5	-1.0	-1.5	-2.0
Falcon	95.8	94.5	77.8	12.8	0.8
Apex	95.0	84.3	43.5	2.8	1.0
Starlight	93.8	77.3	59.3	2.3	0.3
Bristol	87.0	68.3	30.5	0.8	0.3
Mean	92.9	81.1	52.8	4.7	0.6

However, this relationship has not been tested

- a) for the cultivar Libravo used throughout these experiments
- b) for seeds of differing size

### 3.3.2 Hypothesis

Seed imbibition and subsequent germination in soil systems are reduced as soil water potential becomes more negative.

### 3.3.3 Materials and methods

Gravimetric soil moisture contents of air-dried samples were determined for the Evesham, Fladbury and Dunnington Heath soil series. Five 3 kg samples of each air-dried soil were hydrated to moisture contents equivalent to -0.2, -0.5, -1.0, -1.5 and -2.0 MPa (Table 3.3), calculated using the water release curves. The water was added as ice, placed between layers of soil to give an even distribution. The soil was left to equilibrate in sealed tubs for four days, mixed and left for a further 24 hours.

Table 3.3: Soil moisture contents determined for the three soils over the range of water potentials investigated.

Water potential (MPa)	Soil series		
	Evesham	Fladbury	Dunnington Heath
-0.2	29.6	28.9	9.6
-0.5	27.4	26.3	8.6
-1.0	26.0	24.8	8.2
-1.5	25.3	24.1	8.0
-2.0	24.8	23.7	7.9

Soil from the equilibrated tubs was transferred to glass jars ( $\approx 100\text{ml}$ ) and sealed with screw top lids. Six sets of jars, each with 6 replicates of each soil water potential / soil type combination were prepared. The two seed sizes were prepared by sieving through a 2mm square mesh endecote sieve. Half the replicates were filled with 100 seeds  $>2\text{mm}$  diameter and the others with seeds  $<2\text{mm}$  diameter.

The jars were sealed and kept on a laboratory bench, under covers to exclude the daylight. The average daily temperature throughout the experiment was  $14^{\circ}\text{C}$  ( $\pm 7^{\circ}\text{C}$ ). Seeds were extracted at 0.5, 1, 2, 3, 5 and 14 days after sowing. One complete set of jars containing six replicates (three of each seed size), for each water potential / soil combination was selected at random at each sample time. The total number of germinated (radicle protruding) and ungerminated seeds were counted in each sample and the percentage germination calculated.

Seed moisture content of ungerminated seeds was determined at 12, 24, 48 and 72 hours after sowing to follow imbibition. Approximately 50 ungerminated seeds were transferred from each jar to a labelled glass vial using tweezers, taking care to remove all the soil from the seed surface. The fresh weight was determined to an accuracy of four decimal places prior to drying to constant weight after which the sample was re-weighed and the moisture content calculated as a percentage of the wet weight. The original seed moisture was also calculated for each seed size using seed from the sieved batches. At 2 and 3 days after sowing moisture contents of germinated seeds were also determined using the same method.

Total potential germination was determined for three lots of 50 seeds for both  $>2\text{mm}$  and  $<2\text{mm}$  seed. Seeds were sown in petri dishes on Whatman No.1 filter paper wetted with distilled water. The seeds were incubated on a laboratory bench at room temperature and re-wetted daily to ensure a water potentials close to zero.

In addition to the main experiment, moisture uptake at water potentials close to zero was measured by determining seed water content on a wet weight basis from seed sown on Whatman No.1 filter paper saturated with distilled water and incubated at  $20^{\circ}\text{C}$ . Samples of 50 seeds were extracted at 15 minute intervals over the first six hours and then 6.5, 7, 8, 10, 13.5 and 21.5 hours after sowing.

### **3.3.4 Results and Discussion**

Seed moisture content in seeds sown on saturated filter paper incubated at  $20^{\circ}\text{C}$  increased from 6% to 42% over the first 8 hours of imbibition (Figure 3.2). This was similar to the response of soyabean seeds reported by Simon (1984) in which an initial rapid phase of water

uptake over the first 5-10 minutes was followed by a slower linear phase lasting 5-10 hours after which imbibition 'slackened off'.

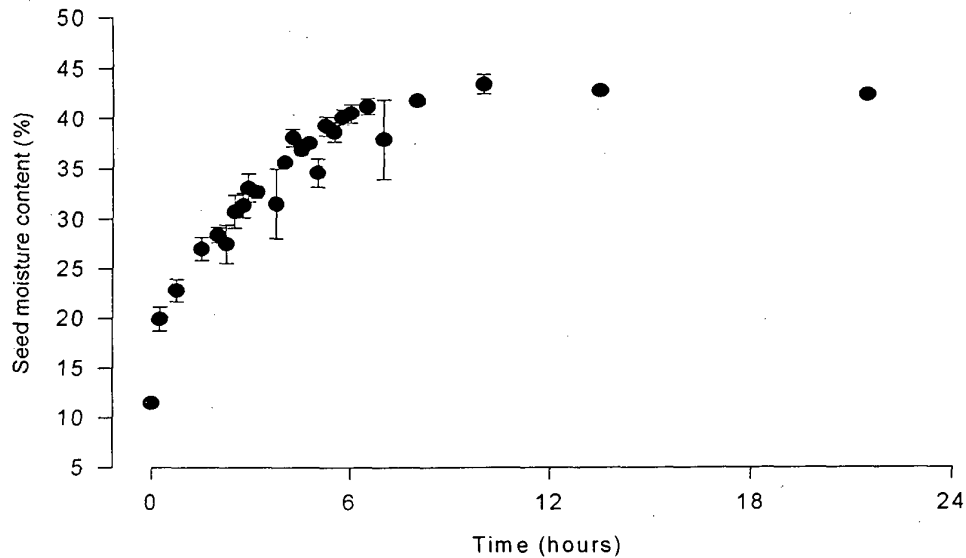


Figure 3.2: Moisture uptake (wet weight basis) in petri dishes with unrestricted water. Error bars indicate double standard errors.

In the soil, at water potentials between -0.2 MPa and 2.0 MPa seeds continued to imbibe water up to 48 hours after sowing after which water uptake was reduced (Figure 3.3). This more gradual period of imbibition where water supply is restricted has been noted in other crop species (Simon, 1984). At 12, 24 and 72 hours after sowing seed moisture content was significantly ( $P < 0.05$ ) higher in the -0.2 MPa treatment compared to the drier soils in both the large and small seed. However, the actual difference was always less than 3 percentage points and there was no statistical difference between the other water potential treatments. This relatively small effect of water potential on imbibition was similar to that found by Williams & Shaykewich (1971) and was partly explained by the fact that the water potential of dry rapeseed is of the order of -100 MPa and consequently the initial driving force for water movement between seed and soil is considerable (Shaykewich & Williams, 1971).

Seed size had a significant ( $P < 0.001$ ) effect on seed moisture at each of the sample times; the smaller seed (<2mm) had moisture contents between 3 and 6 percentage points higher than the larger seed (>2mm) at comparable water potentials (Figure 3.3). Overall, the moisture contents of ungerminated seeds at 72 hours after sowing were approximately 7-10 percentage points lower than the maximum seed moisture contents measured in the petri dish experiment where water was unrestricted.

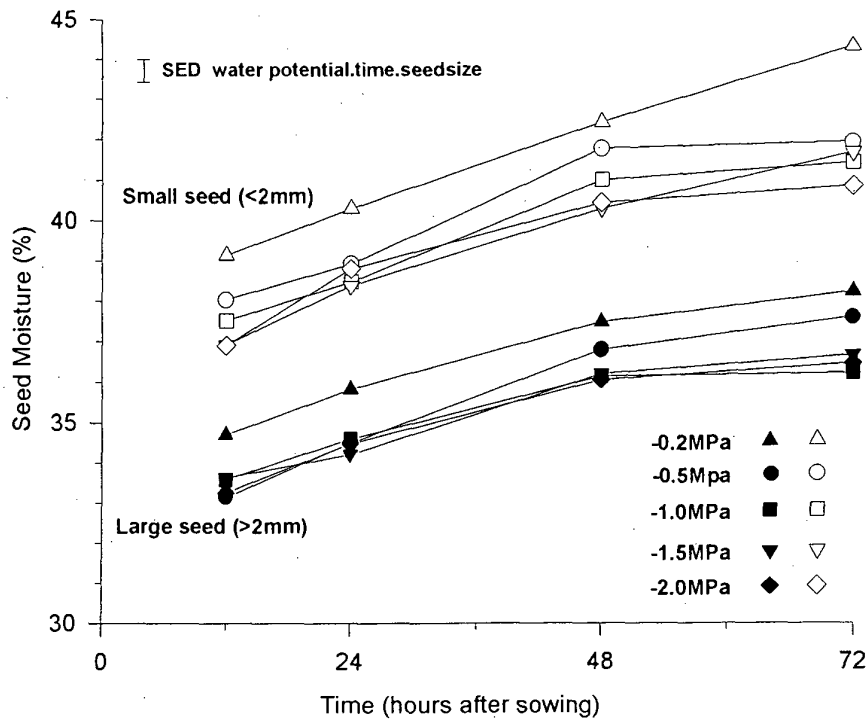


Figure 3.3: Seed moisture content (%) of ungerminated seed > and < 2mm between 12 and 72 hours after sowing at matric potentials between -0.2 MPa and -2.0 MPa. Data points are mean of nine values, the error bar indicates the SED for the highest order interaction.

Despite the small differences in seed imbibition, the onset of germination was slower at lower water potentials, as reported by Williams & Shaykewich (1971), although the extent of the delay in onset and magnitude of the effects were different in each soil type (Figure 3.4). Germination was generally slower in smaller seed (<2mm) but did not statistically affect the final germination percentage compared to large seed (>2mm) measured 14 days after sowing and so final germination percentages from each seed size were pooled.

The average moisture content of germinated seeds (measured at radicle protrusion) was 40% in the large seed compared to 43% in small seed. These values fall within the range of minimum moisture contents for germination of crop species determined by Hunter & Erikson (1952): rice 26.5%, maize 30.5%, sugarbeet 31% and soyabeans 50%.

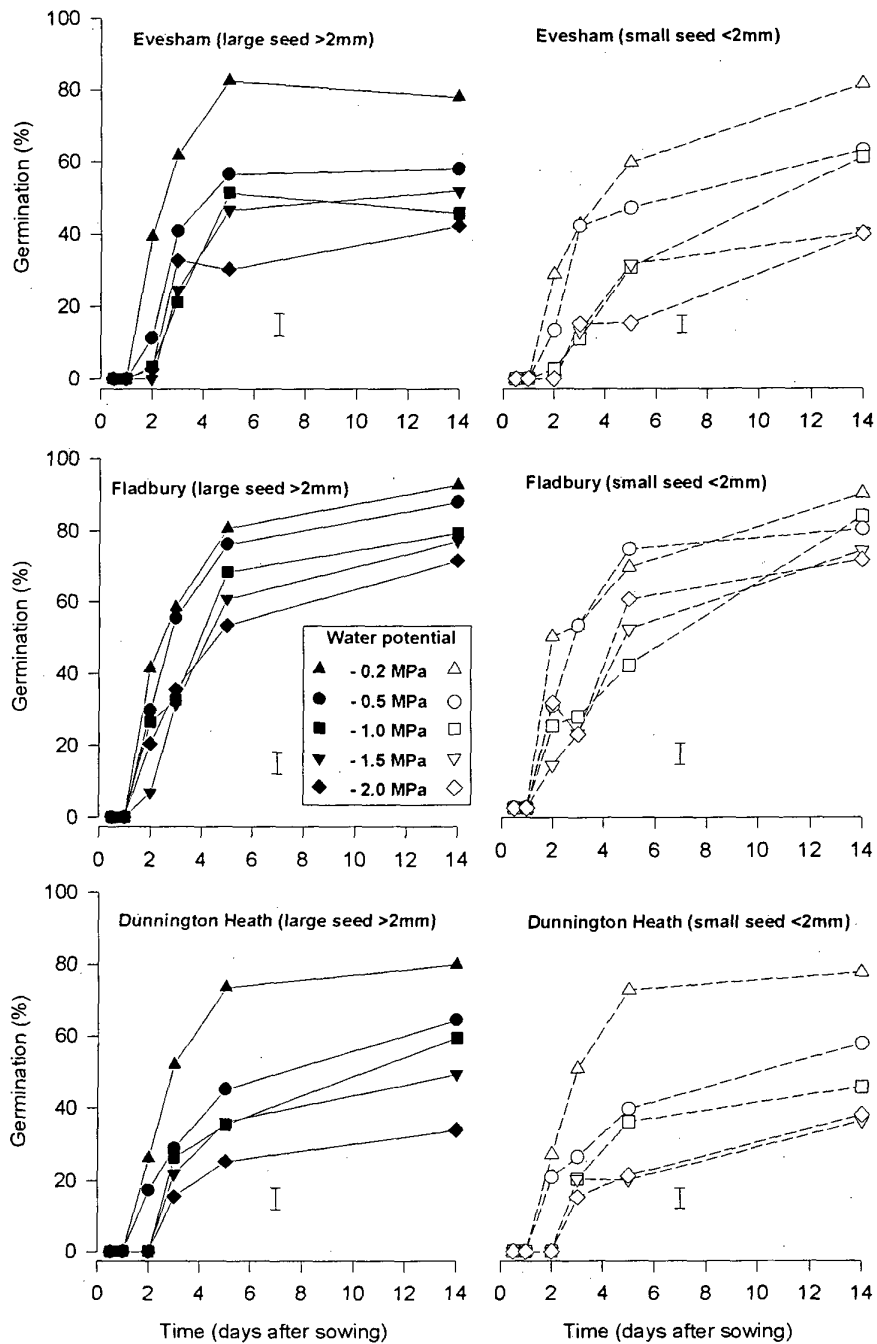


Figure 3.4: Effect of water potential on rate of germination of large(>2mm) and small (<2mm) seed, measured in three soil types.

Water potentials were imposed by preparing soils at different moisture contents calculated from water release curves. Data are mean of three values, the error bar indicates the SED for the highest order interaction.

Final germination percentage decreased significantly ( $P < 0.001$ ) at increasingly negative water potentials (Table 3.4) as reported by Williams & Shakewich (1971). However, the absolute size of the reduction varied between the three soil types. The reduction was similar in the Evesham and Dunnington Heath soils, but the rate of decline in the Fladbury soil was much lower. The variation between soils was attributed to errors arising from the determination of the water release curves, and/or the fluctuations in soil moisture. The difference in soil moisture between the three highest water potentials was less than 1.3% (w/w) in the Fladbury and Evesham soils and less than 0.4% (w/w) in the Dunnington Heath. Such small absolute differences combined with water cycling resulting from temperature gradients in the glass jars could have caused localised variation in water potentials.

Table 3.4: Percentage germination at increasingly negative matric potentials, in soil systems, compared to 'potential' from a standard laboratory germination test. Water potentials were imposed by preparing soils at different moisture contents calculated from water release curves.

Soil Series	potential germination	Water Potential (MPa)				
		WET	→→→→→→→→→	→→→→→→→→→	→→→→→→→→→	DRY
		-0.2	-0.5	-1.0	-1.5	-2.0
Evesham	91	79	61	53	43	36
Fladbury	91	90	83	80	74	70
Dunnington Heath	91	80	61	53	46	41
Mean	91	83	68	62	54	49

SED 6.29 (59df) except when comparing means 3.63 (59df)

In this experiment there was no distinct cut off point in total germination in relation to water potential contrary to the data of Pekrun & Lutman (Personal Communication) and Williams & Shaykewich (1971) who both showed a distinct drop at -1.5 MPa. Taking these data into consideration and the fact that in two soils in the current experiment germination fell below 50% at -1.5 MPa, this water potential was adopted as a practical threshold limit for germination. Using this threshold, the critical moisture contents for the five soils tested in Section 3.3 was calculated from the water release curves (Table 3.5).



Table 3.5: Moisture content at -1.5 MPa for the five soils tested in Section 3.2

Site	Soil Series	Textural class	Clay content (%)	Moisture content at -1.5 MPa
Drayton	Evesham	Clay	52	25
Kneesall	Worcester	Silty Clay	30	14
Lidlington	Denchworth	Clay loam	32	16
Univ. of Nottingham Field 8	Fladbury	Clay	47	24
Univ. of Nottingham Field 9	Dunnington Heath	Sandy loam	14	8

Using these critical soil moistures for each of the soils, regression analysis comparing linear, quadratic and exponential expressions to describe the critical soil moisture level from the percentage clay content of the soil were calculated. The linear model provided the best fit and accounted for 97% of the variation (Equation 3.4). This equation was used to calculate the critical water contents for generic soil types (Table 3.6).

Equation 3.4: Linear equation describing moisture content at -1.5 MPa from percentage clay content.

$$\text{Moisture content at -1.5 MPa} = \% \text{ clay} \times 0.5 - 0.4$$

Table 3.6: Soil moisture at -1.5 MPa in relation to clay content calculated using Equation 3.4.

Soil textural class	Average clay content (%)	Calculated soil moisture content (%) at -1.5 MPa
Sandy loam	10	5
Silt loam	15	7
Sandy clay loam	30	15
Silty clay	35	17
Clay	50	25

This provides a mechanism by which growers could ascertain the potential for germination within an uncultivated soil using a simple moisture test. This would be valuable where soil moisture was marginal and choice of cultivation implement could affect moisture conservation. The soil water matric potential, at a given moisture content, is dictated by the soil textural

qualities - the proportions of clay, silt and sand. While this property is beyond the control of the grower, the seed/soil interface can be manipulated through aggregate size. Small aggregates are more close packed than larger aggregates and so have a greater area of contact with the seed, facilitating the capillary movement of water and reducing the matric potential (Hadas & Russo, 1974a). Fine aggregates also reduce evaporative losses at the soil surface (Braunack & Dexter, 1989a). However, the desire to create a fine seedbed must be balanced with the prevailing conditions since, if cultivations are required to create a fine tilth, then the act of cultivating will in itself cause moisture loss and offset any advantage conferred by smaller aggregates. This is particularly important where soil moisture levels are 'marginal' defined in this experiment as soil moistures equivalent to a water potential of -1.5 MPa. In contrast, if the soil moisture is high then production of a fine seedbed may be unnecessary (in relation to germination) and in poorly drained soils (e.g. non-calcareous, low organic matter) might predispose the seedbed to surface waterlogging, since fine aggregates are more prone to dispersion and capping (Davies *et al.* 1993).

This interpretation may explain observations made during cultivation experiments at Lidlington 1991 (McWilliam *et al.* 1995) where different cultivation strategies resulted in very different soil moistures at drilling, exacerbated by a week without rainfall. The calculated critical threshold soil moisture on the Denchworth series soil was 16%, whereas the average soil moisture at drilling on the uncultivated direct drilled treatment was 15%; discing reduced this to 14% and ploughing to 7%. Emergence was recorded in the direct drilled plots before further rain, but no germination was evident in the disced or ploughed plots (Figure 3.5). The rainfall events totalling 7mm (14 and 16 September) were sufficient to elevate the moisture content of the disced plots above the critical range and emergence was recorded shortly after. However, emergence in the ploughed plots was not triggered by these rainfall events and exploratory excavations revealed that germination had not occurred. Emergence in the ploughed plots was not recorded until after a 43mm rainfall event on the 26 September.

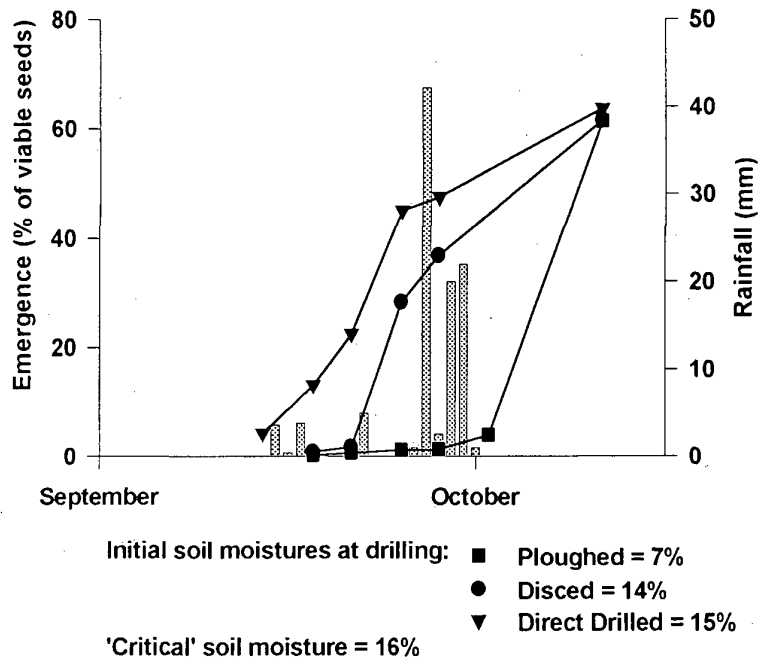


Figure 3.5: Seedling emergence in relation to initial soil moisture and subsequent rainfall (Lidlington 1991, Denchworth series soil).

Although soil texture is a key factor in controlling water transfer where a seed is totally encased and in direct contact with soil, seeds are often drilled in to seedbeds containing large loosely packed aggregates, for example when heavy soils are cultivated in very dry conditions and large platy aggregates are left near the surface. As a result seed soil contact can be reduced and hence the area for water transfer is reduced. The following section describes a controlled environment experiment to quantify the effect of aggregate size on water uptake and germination at marginal moisture contents.

### 3.4 THE EFFECT OF AGGREGATE SIZE AND SOIL MOISTURE ON GERMINATION

#### 3.4.1 Background

Aggregate size influences seed/soil contact and so alters the matric potential. If soil water potential is low, increasing aggregate size can limit water transfer between soil and seed (Collis-George & Hector, 1966). To maximise seed/soil contact Hadas & Russo (1974a, b) suggested that aggregates should be one-fifth to one-tenth the size of the seed. However, for small seeded crops, such as oilseed rape, this would require very fine particles which would be highly erodible (Braunack & Dexter, 1989b; Davies *et al.* 1993). The optimal aggregate sizes for various crop species including cereals, sugar beet, soyabean and cotton was reviewed by Braunack & Dexter (1989b) and indicated a range from <1 mm to 4 mm but no data for oilseed rape was presented. In general, it has been suggested that ideal conditions for a seedbed are produced by aggregates not less than 0.5 - 1 mm and not coarser than 5 - 6 mm (Russel, 1973).

The water requirement for germination in oilseed rape was described in Section 3.3 and showed that water potentials below -1.5 MPa severely reduced germination. However, these measurements were made in soil where aggregates were less than 2mm in diameter. The two years of cultivation trials described by McWilliam *et al.* (1995) showed the range of aggregate distributions which can occur in the field; the effects of aggregate size, more representative of seedbed structures in the field, on water transfer have not been measured in oilseed rape.

#### 3.4.2 Hypothesis

Increasing aggregate size reduces seed soil contact and consequently impedes germination in soils with low water potentials.

#### 3.4.3 Materials and Methods

Approximately 100 litres of Fladbury series soil was collected from the University of Nottingham Farm (Field 8) from the same area sampled for analysis of water release characteristics (Section 3.2). The soil was air dried for a month before sieving to produce four aggregate fractions: 0-3.4mm, 3.4-11mm, 11-17mm and 17-23mm. The soil fractions were then force dried in an oven at 30°C to constant weight. Twenty 2.0 litre plastic tubs were each filled 2/3 full with a single aggregate fraction to give a total of eighty tubs. The experimental design was a factorial combination of aggregate size (0-3.4mm, 3.4-11mm, 11-17mm and 17-23mm) and soil moisture contents (14, 16, 18, 20, and 22%) each replicated four times.

The volume of water required to achieve the correct moisture content, on a dry weight basis, was calculated from the dry weight of the soil in each individual tub. The two smallest aggregate fractions were hydrated by stirring the soil whilst misting the surface with a hand held sprayer; the larger fractions were misted layer by layer to prevent loss of aggregate structure. The tubs were subsequently sealed and left for five days in the laboratory for the water to equilibrate.

On the sixth day, 150 seeds were sown into each tub. Only seed > 2mm in diameter was used to reduce variation in water uptake, identified in Section 3.3. To ensure an even placement of seed, different methods of sowing were used for each aggregate size. For the smallest aggregates (<3.4mm) a layer of soil approximately 2cm deep was removed, the seeds placed evenly onto the exposed layer, avoiding the perimeter of the tub, and the soil replaced. In the case of the two intermediate aggregate fractions (3.4-11mm and 11-17mm), the seeds were placed on the surface and the tubs shaken until all the seeds had trickled down between the aggregates. For the largest aggregates (17-23mm), the seeds were sown into the inter-aggregate spaces.

All the tubs were sealed and incubated in a controlled environment growth room at 20°C in darkness. The tubs were vented daily to alleviate any CO<sub>2</sub> build up and after 28 days the tubs were tipped out and total number of germinated seeds recorded.

#### **3.4.4 Results and Discussion**

The range of moisture contents used was lower than ideal. The highest soil moisture content, 22%, was two percentage points lower than the moisture content equivalent to -1.5 MPa (from the water release curves). The determination of the water release characteristics required special equipment which was not available until after the experiment had been conducted and so it was only possible to estimate the moisture range in relation to those moisture conditions experienced in marginal conditions in the field.

Overall, total germination increased significantly ( $P < 0.01$ ) as moisture content increased from 14% to 22%. At every moisture content, the largest two aggregate fractions produced the highest germination, and at soil moisture contents of 16, 18 and 20% this effect was significant ( $P < 0.01$ ) (Figure 3.6). This result was contrary to the stated hypothesis and previous studies, reviewed by Braunack & Dexter (1989b). However, observations suggest that this was partly an artefact of the experimental design since water was redistributed within the tubs i.e. water evaporated from the soil, condensed on the sealed lid and then dripped back onto the aggregates resulting in localised pockets of high moisture contents. This was more pronounced in the larger aggregates due to the greater surface area for evaporative loss and the greater dispersion of the water due to the open structure.

In the enclosed environment this acted to increase the moisture available to the seed but clearly in an open system (i.e. a field) this would not confer the same advantage and would increase evaporative losses (Braunack & Dexter, 1989b).

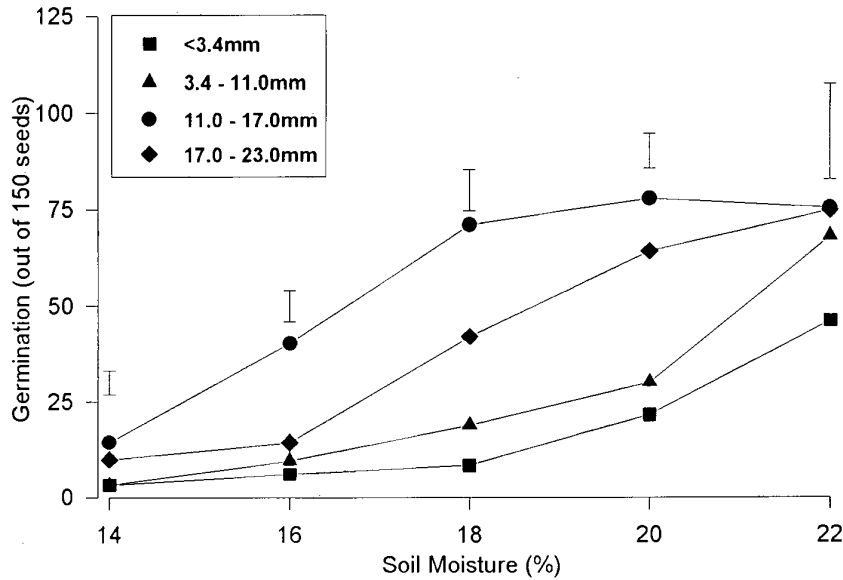


Figure 3.6: The effect of aggregate size and soil moisture on germination.

Data are means from four replicates, error bars indicate SEDs (9df).

Within the bounds of time and resources available it was not possible to overcome these problems in the experimental design and so this line of experimentation was abandoned. Instead, the effects of aggregates were examined in small field experiments which encompassed not only the effects of restricted water supply but also the physical impedance that large aggregates impose. It is important to consider that for oilseed rape which is a very small seed, the size of the aggregates not only affects the potential for water supply but also may present a physical barrier to emergence. This would be most likely on heavy soils in dry conditions as large platy aggregates are left near the surface. The following section reports an analysis of the potential effects of aggregate size distribution on emergence of oilseed rape, first where water was marginal and second where water was plentiful.

### **3.5 THE EFFECT OF AGGREGATE SIZE ON SEEDLING EMERGENCE UNDER FIELD CONDITIONS**

#### **3.5.1 Background**

Large aggregates in the surface layers of soil are known to reduce seed soil contact and limit water supply but may also present a physical barrier to emerging hypocotyl. In order to test the effects of aggregate size on emergence of oilseed rape under field conditions, three seedbeds were prepared which contrasted in aggregate size distribution in the surface 5cm layer of soil.

#### **3.5.2 Hypothesis**

The proportion of 'large' aggregates in a seedbed dictates emergence, due to restricted water transfer where soil moisture is marginal and/or by physical impedance of the hypocotyl.

#### **3.5.3 Materials and methods**

The experiment was conducted on an alluvial non-calcareous clay (Fladbury series) in Field 8 of the University of Nottingham Farm. Plots measuring 4m × 13m, replicated across three blocks were prepared by ploughing to a depth of 20-25cm and then rotavating either 1, 2 or 4 times to prepare three seedbed treatments with contrasting aggregate distributions (Course, Medium and Fine). Each plot was rolled with a Cambridge roll to reduce potential differences in drilling depth associated with different levels of consolidation. Plots were drilled on the 6 October 1995 using an Øyjard plot drill, at a seed rate of 200 viable seeds m<sup>-2</sup>.

To measure the aggregate distribution, four soil samples were removed from each plot by randomly inserting a steel template measuring 20cm × 20cm × 5cm and removing the soil into a metal tray. After air drying in the laboratory, the aggregate distribution was determined by passing the soil through a series of sieves to determine the percentage by weight of soil in each fraction.

Emergence was monitored daily in four 0.72 m<sup>2</sup> quadrats positioned along the length of the plot. Seedlings were counted and removed once they had emerged (cotyledons fully expanded).

Measurements of soil moisture were made on 7, 13, 16 and 23 October and showed that the soil moisture fell from 24% to 19% over the two week period following drilling and was below the critical threshold (24%) for most of the period (Table 3.7). This provided a measure of the effect of aggregate size on emergence, where water was marginal. Only 11.6mm of rain fell in the following two week period during which time few seedlings emerged in any treatment. In order to investigate the effect of aggregates where water was not limiting, 10mm of water was

applied to each quadrat area on 7 November, using a watering can and subsequent emergence monitored.

Depth of sowing was assessed by excavating five adjacent rows in the main plot area and randomly selecting five seed locations in each row. The depth was measured as the distance from the seedbed surface to the seed or if the seed had germinated, the distance from the seedbed surface to the margin between the stem and root.

When emergence ceased, the proportion of seeds which had germinated but failed to emerge, was estimated by excavating seeds in two 30cm row lengths within each quadrat.

The results were expressed as seedlings which emerged prior to irrigation, seedlings which emerged following irrigation and those which germinated but failed to emerge. The remaining unaccounted seeds, from the average of 144 seeds per quadrat, were classified as not recovered (ungerminated).

#### **3.5.4 Results and Discussion**

The proportion of large aggregates >23mm within the seedbed decreased significantly ( $P<0.01$ ) with the number of passes with the rotavator, whilst the proportion of small aggregates <3.4mm increased significantly ( $P<0.05$ ) (Figure 3.7). Depth of sowing was similar in the Coarse, Medium and Fine treatments at 3.5cm, 3.1cm, and 3.2cm respectively.

The soil moisture of the Fine plots recorded the day after drilling (7 October) was 26% (Table 3.7) indicating a water potential of -0.5 MPa (Section 3.2). Thus, germination would not have been limited by water at this stage (Table 3.4). However, the seedbed dried in the following week and by 13 October, the Fine and Medium seedbeds had soil moisture contents of 24%, equivalent to the critical -1.5 MPa level for the soil and the Coarse seedbed was only 21%, well below the -2.0 MPa level. On this date, the Coarse seedbed was significantly drier than both the Medium or Fine treatments. In the following 10 day period, only 1.9mm of precipitation fell and all the seedbed moisture contents fell to 19% by 23 October. The application of 10mm water on 7 November elevated soil moisture content by 7-9 percentage points to 26-28%, equivalent to -0.5 MPa (Table 3.7).



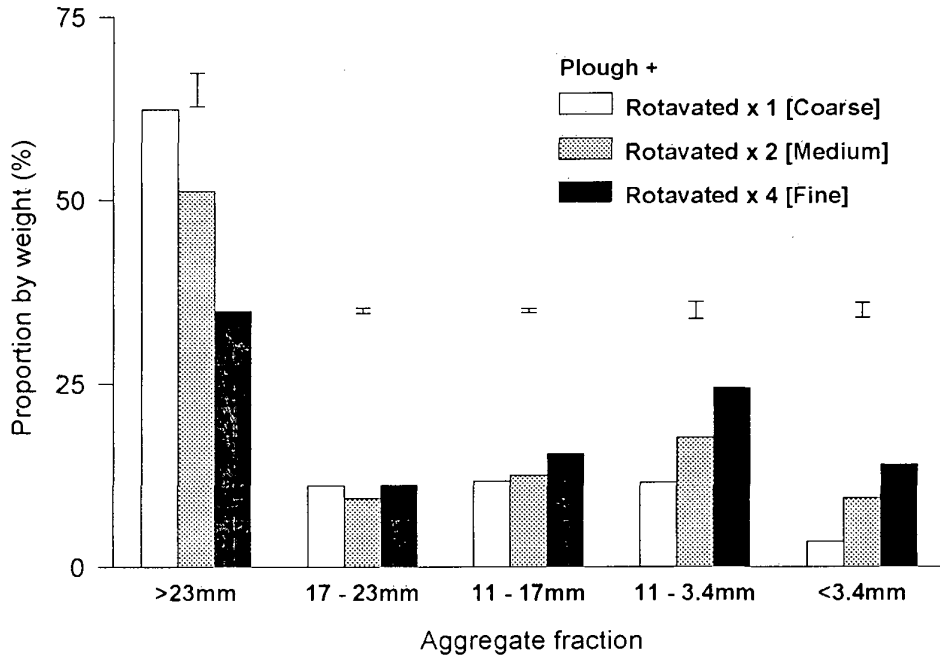


Figure 3.7: Comparison of aggregate size distribution in three seedbeds created by increasing the number of passes with a rotavator.

Data are means of three replicates, error bars indicate SEDs (4df).

Table 3.7: Comparison of gravimetric soil moistures over time, in the top 5cm layer of the soil profile in seedbeds with differing aggregate distributions.

Treatment	7/10/96	13/10/96	16/10/96	23/10/96	7/11/96 (post irrigation)
Coarse	not measured	21	22	19	26
Medium	not measured	24	22	19	26
Fine	26	24	22	19	28
Prob	-	0.04	ns	ns	ns
SED (8df)	-	0.8	1.1	1.3	1.0

Prior to the irrigation event, between 5 and 17% of seeds emerged, but there was no statistical difference between seedbeds (Table 3.8) i.e. the higher soil moisture in the Medium and Fine seedbeds on 13 October did not improve emergence. Following the application of 10mm of water, which raised the soil moisture content above the -1.5 MPa threshold,

approximately one-third of the seeds drilled emerged, irrespective of the seedbed structure. Overall, aggregate size did not significantly affect the total number of seeds which emerged.

The number of germinated seeds which failed to emerge was higher in the Coarse and Fine seedbeds compared to the Medium treatment, but this was not statistically significant. Overall, the combined total of germinated and/or emerged seeds accounted for between 52 and 59% of seeds sown, with no statistical difference between the Coarse, Medium and Fine seedbeds.

Table 3.8: The fate of seeds drilled into seedbeds contrasting in aggregate distribution, as a percentage of viable seeds sown.

Data are averages of three replicates.

	Seedbed description			Prob (4df)
	Coarse	Medium	Fine	
Emerged before irrigation	6	17	5	NS
Emerged after irrigation	29	35	36	NS
Total emergence	35	52	41	NS
Germinated but failed to emerge	17	7	17	NS
Germinated + Emerged	52	59	58	NS
unrecovered / Ungerminated (calculated)	48	41	42	NS

The high percentage of unrecovered / ungerminated seeds may have been due to secondary dormancy being induced; Pekrun, Lutman & Baeumer (1997a) identified that seed exposed to low water potentials may become dormant. A more probable explanation is that germination was initiated by the initial moisture content but the seedlings subsequently desiccated, as observed in sugarbeet (Gummerson, 1986). Although the timing and effect of desiccation on oilseed rape are not known there is anecdotal evidence which indicates that drilling into a moist seedbed which subsequently dries results in dramatic losses, which would account for the large proportion of ungerminated seeds. This has not been studied in detail and is investigated in the next section.

### **3.6 TIMING OF DESICCATION IN RELATION TO SEED AND SEEDLING FATALITY**

#### **3.6.1 Background**

Soil moisture in the field can fluctuate widely, especially in the upper layers of the seedbed in response to drainage, evaporative demand and precipitation (Brady & Weil, 1996). The emergence phase is reliant on a maintained water supply since both the root and shoot are sensitive to desiccation. El-Sharkawi & Springuel (1977) reported that radicle and plumule elongation in wheat and barley exhibited a linear reduction with increasing solute potential, down to 30% of control at -1.5 MPa. Emergence in oilseed rape has also been shown to be restricted at water potentials less than -0.25 MPa (Rao & Dao, 1987). However, the effect of restricted water supply / desiccation following initial unrestricted supply, more typical of the fluctuating conditions in the field, has not been investigated.

#### **3.6.2 Hypothesis**

Desiccation events during germination and emergence kills seeds/seedlings.

#### **3.6.3 Materials and methods**

Fifty seeds (cv. Libravo) were placed in each of eight, 9cm diameter petri dishes lined with Whatman No1 filter paper and 5cm<sup>3</sup> of distilled water was added. The petri dishes were kept in a growth cabinet at 17°C±5, with 12hr photoperiod. This process was repeated at 24hr intervals and finally 12hrs to give seven stages of development: 12, 24 and 36 hours after first imbibition and seedlings with radicle protruding, radicle 1cm long, cotyledons exposed and cotyledons expanded. To minimise the variation within each development stage, seedlings were interchanged from the eighth replicate to produce seven replicates with 50 uniform seedlings. To retain a statistical balance one petri dish from the seed 12, 24 and 36 treatments was discarded.

Of the seven replicates, four were selected at random for drying back and the remaining three retained as controls. Desiccation was imposed by removing the seeds/seedlings onto filter paper to remove water from their surface and then placing them in a petri dish with dry filter paper. The open petri dishes were held for six hours in a cabinet at 18°C with forced air movement generating a pan evaporation of  $7.6 \times 10^{-3} \text{ cm}^{-3} \text{ cm}^{-2} \text{ hr}^{-1}$ , equivalent to  $0.05 \text{ cm}^{-3} \text{ cm}^{-2}$  over the six hour period. A sub-sample of 15 seeds was taken both before and at the end of the drying phase to determine the moisture content.

Following drying, the seeds/seedlings were re-wetted with distilled water and held at 20°C for seven days with additional water added as necessary. At the end of this period, the number of seeds which germinated from the seeds desiccated after 12, 24 and 36 hours was determined. In the treatments desiccated at radicle protrusion, radicle 1cm long, cotyledons exposed and cotyledons expanded, the length and condition of the hypocotyl and radicle were compared in relation to the controls. Seedlings with abnormal (stunted and/or discoloured) radicles or hypocotyls were recorded as non-viable.

### 3.6.4 Results and discussion

Prior to radicle protrusion, seed viability was not reduced as a result of a single hydration / desiccation cycle but was slightly improved (Table 3.9). In contrast, desiccation after radicle protrusion resulted in a highly significant reduction in seedling viability. This was associated with a high proportion of seedlings which continued to show cotyledon growth after returning to water, but which had stunted roots.

Table 3.9: The relationship between time of desiccation and production of viable seedlings taking account of the initial and post desiccation seed moisture content.

Time after sowing (h) / development stage when desiccation imposed	Moisture content (%) pre-drying	Moisture content (%) post-drying	Difference (percentage points) in production of viable seedlings (cotyledons expanded) between desiccated and non-desiccated seeds / seedlings
12	40	7.7	+2
24	44	7.9	+12
36	36	8.0	+17
Radicle Protrusion	55	6.0	- 78
Radicle 1cm	69	15.0	-78
Cotyledon Exposed	79	20.0	-95
Cotyledon Expanded	85	34.0	-91

Within the field environment, desiccation would probably occur more gradually and may fluctuate between wetting and drying cycles. However, these data clearly show the risk of seedling loss if desiccation events occur in the period post radicle protrusion.

The greatest fluctuation in soil moisture occurs in the upper horizons of the seedbed. Thus, deeper drilling may provide a strategy to reduce the risk of desiccation in dry seedbeds, an approach suggested by Håkansson & Von Polgár (1984) for small seeded crops. However, a systematic analysis of the effects of sowing depth on emergence of oilseed rape has not been reported in the literature.

### **3.7 THE EFFECT OF SOWING DEPTH ON SEEDLING EMERGENCE**

#### **3.7.1 Background**

Seedling emergence results from cell division and expansion in the hypocotyl. Both are energy dependent processes (Simon, 1984). While the seedling is underground and not able to photosynthesise, energy is provided from respiration of stored reserves. In the case of oilseed rape, these are predominantly oils (Simon, 1984). There is a finite supply of energy that the seed can produce, if the stored reserves are exhausted before the seedling becomes heterotrophic (starts producing its own energy by photosynthesis), then the seedling will die. The total amount of stored reserves depend on the seed's size and the amount of energy from a given quantity of substrate (oils or carbohydrate) which is dependent on the respiratory pathway; anaerobic respiration dramatically reduces the efficiency of conversion.

Previous studies which have examined the effect of depth of sowing on emergence of oilseed rape have determined optimal depths of 1.5cm (Nuttal, 1982) and 1-3cm (Loof, 1972) under field conditions. However, the pattern of reduction in emergence from increasing sowing depth has not been quantified under standard conditions.

#### **3.7.2 Hypothesis**

Increased depth of sowing results in an exponential decline in emergence.

#### **3.7.3 Materials and methods**

In order to minimise the possible influence from differences in aggregate size bulk densities, horticultural sand was used at a uniform bulk density of  $1.1 \text{ g cm}^{-3}$ . The sand was watered to saturation point and allowed to drain for 24 hours prior to commencing the experiment. Immediately before sowing, the sand was thoroughly mixed to ensure a uniform moisture content

Seeds were sown at 2, 3, 4, 6.5, 10 and 15 cm deep in plastic drainage pipes 12cm in diameter. Each pipe was placed upright onto a perforated polythene covered mesh to allow adequate drainage whilst preventing the sand from being washed away during watering. A 3cm

layer of sand was placed in the bottom of each 'pot' and 200 seeds sown on top, the appropriate depth of sand was then added. Four replicates of each depth were arranged in four randomised blocks in a growth room at 20°C with a 12h photoperiod. Emergence (cotyledons fully open) was monitored daily; seedlings were decapitated as they emerged to prevent counting errors.

### 3.7.4 Results and Discussion

Figure 3.8 shows the effect of sowing depth on percentage. The fitted curve was derived from a regression analysis, using appropriate routines in Genstat 5 (Equation 3.5). The fitted curve accounted for 95.8% of the variance in the data.

Equation 3.5: The relationship between sowing depth and emergence.

$$\text{Predicted emergence} = -1.19 + \frac{80.6}{(1 + \exp(0.09 \times (X - 74.6)))}$$

where X = depth of sowing (cm)

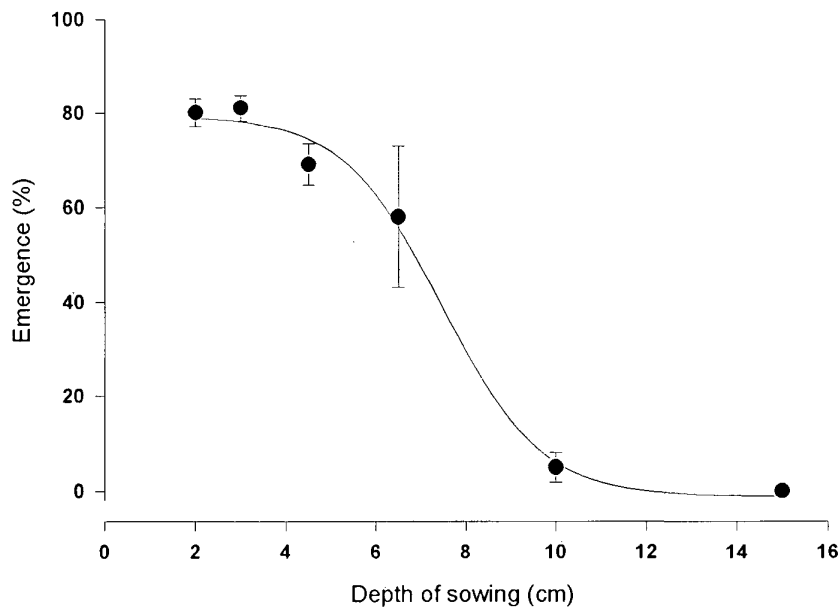


Figure 3.8: Seedling emergence (%) from increasing depths of sowing in horticultural sand.

Fitted curve calculated from regression analysis (see Equation 3.5). Data are means of three replicates, error bars indicate double standard errors (3df).

At depths less than or equal to 2cm, predicted emergence was 79%, increasing depth to 5cm reduced emergence to 71%, but at 6cm it dropped to 63%. The implication is that seeds

should be drilled at depths less than 5cm and ideally less than 3cm. This concurs with the findings of Loof (1972) and Nuttal (1982).

As well as limiting the overall proportion of seeds which emerged, deep sowing also increased the time that seedlings spent underground. This has been shown to increase the risk of fatalities from disease and biotic factors (Harper, 1983). To quantify the time penalty for deep sowing, the thermal time to reach 50% of maximum emergence was calculated: time in days to reach 50% emergence multiplied by the temperature of the surrounding medium (20°C, base 0°C). Below 3cm, the thermal requirement for 50% emergence increased by approximately 15 °C d cm<sup>-1</sup> (Table 3.10). It is probable that the thermal requirement is likely to be higher in clay soils where cohesion between particles creates greater resistance to the emerging hypocotyl than sand (Davies *et al.* 1993).

Table 3.10: Thermal time to 50% emergence in relation to sowing depth in a uniform medium.

Depth (cm)	Thermal time (°C d) to 50% emergence	Standard error
2.0	129	2.2
3.0	129	4.2
4.5	151	3.4
6.5	186	11.1
10.0	243	2.5

Although these factors provides a baseline from which to predict emergence, they do not take account of the resistance to growth that the growing medium exerts. This mechanical impedance is dictated by the soil type and bulk density. Where bulk density is high, resulting from compaction and/or crusting of the soil surface, emergence can be restricted (Davies *et al.*, 1993). The following section examines the relationship between soil compaction, soil type and the supply of energy available to the seed (seed size).

## **3.8 THE EFFECTS OF SOIL BULK DENSITY, SOIL TYPE, AND SEED SIZE ON SEEDLING EMERGENCE**

### **3.8.1 Background**

Soil structure refers to its aggregate size distribution and the shape and packing of the aggregates (Russell, 1973). These characters determine bulk density i.e. soil weight per unit volume, which is a measure of soil consolidation or, if the bulk density is very high, compaction (Soane, Campbell & Dickson, 1984). Over-compaction of seedbeds is considered an increasing problem, associated with heavier tractors and implements now used in modern agriculture (Barnes, Carlton, Taylor, Throckmorton & Vandenberg, 1971; Eriksson, Hankansson & Danfors, 1974; Soane, Blackwell, Dickson & Painter, 1981). The surface structure of the soil can also be destroyed by the action of rain on unstable aggregates which results in a close packed cap which can impede emergence (Brady & Wiel, 1996).

Compaction and capping in the upper levels of the seedbed restricts hypocotyl and radicle extension (Davies *et al.* 1993). Reduced emergence of cereals where surface soil has a high bulk density and strength has been widely reported (Chancellor, 1976 (Cited by Lynch & Elliot, 1984); Taylor, 1971). Kubota & Williams (1967) found that the effect of compaction on emergence of cereals was related to soil type; a set level of compaction reduced emergence of spring barley by 15% on a sandy loam, 20% on a silty loam but by 53% on a clay.

It has been suggested that where seedbed conditions are 'unsuitable' larger seed can improve emergence (Håkansson & Von Polgár, 1984) and seed size in oilseed rape has been positively correlated with emergence vigour (Major, 1977). However, there are no reported studies of the effects of surface compaction on oilseed rape emergence nor the relationship between seed size and bulk density on emergence.

### **3.8.2 Hypothesis**

Increasing soil bulk density reduces emergence of oilseed rape seedlings, the reduction being more pronounced in clay soils and with small seed with fewer reserves.

### **3.8.3 Materials and Methods**

Two experiments were conducted to study the effects of soil bulk density, soil type and seed size on seedling emergence. The experimental procedure was based closely on that described by Mulholland (1994). Soil was passed through a 1.5cm sieve and stones removed prior to being oven dried at 85°C to constant weight. The soil was then rehydrated to 10% W/W. The soil was compacted within plastic tubes measuring 15cm in length with an internal diameter of 7cm.



Specific bulk densities were achieved by compacting a predetermined weight of soil within a known volume using an Instron to apply the necessary force. Compacting was performed in layers to ensure even bulk densities were achieved.

The first experiment was conducted using the sandy loam soil (Dunnington Heath Series) dug from the surface layers of Field 9 on the University of Nottingham Farm. Five different bulk densities were compared, 1.1, 1.4, 1.5, 1.6 and 1.7 g cm<sup>-3</sup>. Seeds were sown 2cm deep by placing them on the surface of the penultimate layer of compacted soil. Two seed sizes, >2mm and <2mm were compared, with seven seeds sown into each tube. After sowing, each tube was weighed and distilled water added to elevate the soil moisture to field capacity, thereafter the tubes were weighed daily and water added as necessary. The tubes were arranged in a completely randomised design, on a growth room bench with a 12 hour photoperiod and a day/night temperature regime of 20/12°C. Emergence (cotyledons fully expanded) was monitored daily.

In the second experiment, the non-calcareous alluvial clay (Fladbury series) from the University of Nottingham Farm, Field 8 was used at bulk densities of 1.1, 1.2, 1.3 and 1.4 g cm<sup>-3</sup>. Lower bulk densities were used because soils with a high clay content have greater colloidal strength than those with a low clay content, which increases the force required to move particles at any given bulk density. The soil type and bulk densities were the only aspects in which the two experiments differed.

#### **3.8.4 Results and Discussion**

At a bulk density 1.1 g cm<sup>-3</sup> there was no significant difference in emergence between soil types. Increasing bulk density significantly ( $P < 0.001$ ) reduced emergence in both soils. In the Fladbury series, containing 47% clay, emergence declined significantly as bulk densities increased from 1.1 g cm<sup>-3</sup> to 1.2 g cm<sup>-3</sup> and at 1.3 g cm<sup>-3</sup>, emergence was almost completely inhibited (Figure 3.9). In the Dunnington Heath sandy loam, with only 14% clay, a significant reduction was found at bulk densities of 1.6 g cm<sup>-3</sup> and above.

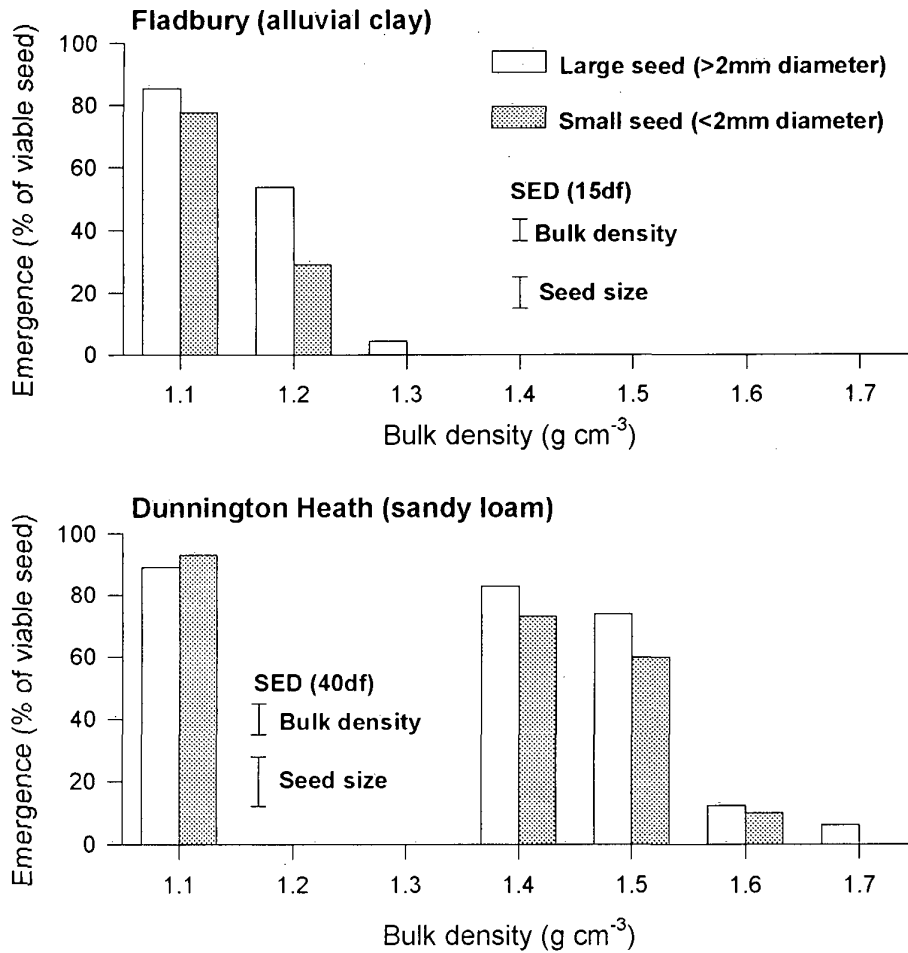


Figure 3.9: Emergence of large and small seeds from 2cm depth at different bulk densities in Fladbury series clay and Dunnington Heath series sandy loam.

Emergence was reduced at a lower bulk density in the clay soil compared to the sandy loam as shown by Kubota & Williams (1967) on spring barley. The explanation for this is that clay soils have more cohesion between soil particles and so require more force (energy) to separate them than sandy soils (Davies *et al.* 1993). In both experiments, the soils were kept at soil moistures equivalent to field capacity; at lower moisture contents the reduction in emergence would have probably been more acute, due to the increase in the soil strength.

On average the small seed (<2mm) produced fewer emerged seedlings at each of the bulk densities, indicating the potential benefit of larger seed where soils are compacted. However, these differences were not significant, irrespective of soil type or bulk density.

### 3.9 CONCLUSIONS

The experiments reported in this Chapter 3 provided quantitative evidence for some of the main physical parameters which govern germination and emergence. These are summarised below:

- a knowledge of the water release characteristics of the soil is necessary to understand water availability.
- seed imbibition in free water occurs rapidly over an eight hour period
- reducing water potentials down to -2.0 MPa does not impede imbibition; however,
- water potentials of -1.5 MPa, or lower, result in a significant ( $P < 0.01$ ) reduction in germination
- using water release curves, a critical moisture content for specific soils can be determined and also for generic soils based on clay content
- water release characteristics help explain observed differences in the field and suggest that a simple moisture test could help growers identify where water is marginal and where more shallow cultivations should be used to conserve water
- aggregate sizes above 23mm (but generally no bigger than 60mm diameter) did not significantly impede emergence.
- seed could survive desiccation provided the radicle had not emerged. Once radicle protrusion was complete, desiccation either killed the seedling or resulted in abnormal root growth.
- sowing deeper than 5cm significantly reduced emergence with optimal sowing depths of 2-3cm.
- thermal time for emergence in horticultural sand increased by approximately  $15\text{ }^{\circ}\text{C d cm}^{-1}$  below 3cm.
- increasing soil compaction significantly reduced emergence from 2cm depth in a Fladbury alluvial clay (47% clay) at bulk densities of  $1.2\text{ g cm}^{-3}$  and above, whereas in a Dunnington Heath sandy loam (14% clay) a significant reduction was only observed at bulk densities of  $1.6\text{ g cm}^{-3}$  and above.

Following this analysis of the individual factors affecting establishment it is now possible to investigate in greater detail the potential reason for failure in the field.

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## 4. FIELD INVESTIGATIONS OF GERMINATION, EMERGENCE AND SEEDLING SURVIVAL

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### 4.1 INTRODUCTION

This chapter examines, under field conditions but in the absence of pests, weeds and diseases, the interaction between the weather and the seedbed. The experimental programme was split into two stages.

Stage I focused on plant emergence and post emergence losses. One of the surprising observations from previous cultivation experiments (McWilliam *et al.* 1995) was the consistent advantage of discing, which left straw mixed in the surface layers, compared to ploughing which inverted the soil and buried the straw away from the seedlings. However, it was not clear whether the advantage of discing resulted because of an interaction with pests or was attributable to improved physical characteristics. To compare overall emergence, post emergence losses and final establishment in seedbeds prepared by ploughing (inversion) or discing (mixing), over a wide range of weather conditions, 11 sequential sowings were made during a 10 month period.

Stage II built on Stage I but also incorporated the findings from the completed laboratory investigations of germination and emergence to examine plant losses in all three phases of establishment. The protocol was also developed to further clarify the effects of cereal residues. Detailed measurements of germination and emergence were made as well as regular counts of surviving plants.

### 4.2 MATERIALS AND METHODS

A total of 16 sowings were made over a 22 month period between October 1993 and July 1995 on field sites located at The University of Nottingham Farm. To maintain continuity with the previous experiments, the winter cultivar Libravo was used throughout; a C1 seedlot was obtained from Nickerson seeds. The seed was dressed with Gamma HCH and Thiram to prevent confounding effects from disease and insect pests.

#### 4.2.1 Stage I

Eleven sowings were made at approximately monthly intervals between 20 October 1993 and 20 July 1994 in Field 2 [SK 512 263]. The Dunnington Heath series medium sandy loam on this site, although not typical of the heavy land where the majority of oilseed rape is grown, was chosen to ensure drilling could be done over a range of weather conditions. The straw from the preceding oat crop was baled and removed leaving just the stubble (approximately 5-10cm long).

From the cultivation experiments (McWilliam *et al.* 1995) and a consideration of how primary cultivations affect the seedbed, three structures were created viz. inverted (Plough - modified forward facing tine), mixed (disc - modified backward facing tine) and uncultivated. Due to limited space, only two seedbeds could be compared over the eleven sowings. Inverted and mixed were chosen because they were most representative of the methods used in commercial practise.

Seedbeds were prepared as follows:

- **Inverted[straw]** - primary cultivation was ploughing to 20cm followed by suitable secondary cultivation, usually using a spring tine.
- **Mixed[straw]** - primary cultivation was by concave discs or rotavator to 10-15cm depth. Where conditions were dry, it was necessary to pre-cultivate with a rigid tine implement to break the surface and facilitate penetration.

Cultivations were performed in the week prior to sowing. Plots measured 4m by 12m, and were arranged in three randomised blocks. Two to seven days before the primary cultivation, wheat straw, chopped into 5cm lengths (using a Teasel Tomahawk straw chopper), was applied by hand at a rate of 9 t ha<sup>-1</sup> to each plot. This ensured a uniform distribution and standardised both the amount and original state of decomposition at each sowing.

Plots were drilled with a Nordsten disc coultter drill and the soil was immediately consolidated with one pass of a Cambridge roll. Each treatment was drilled at a seed rate calculated to give 200 viable seeds m<sup>-2</sup>.

The 1000 seed weight was calculated prior to the first sowing by randomly sampling seed from the top, middle and bottom of the seed sack, giving three samples of approximately 30g. The number of seeds in each sample was counted using an electronic seed counter (Decca Mastercount, London, UK) and their weight recorded.

The germination percentage was measured bimonthly so that any deterioration in seed viability could be corrected by increasing the seed rate accordingly. On each occasion, three random samples of 50 seeds were placed in petri dishes lined with Whatman No. 1 filter paper

moistened with 5ml of distilled water. The petri dishes were covered to exclude light and incubated in a laboratory with nominal temperature range of 10-25°C. Each dish was inspected daily, re-wetted as necessary and any germinated seeds (radicle visible) recorded and removed. Plant counts were made for two weeks or until no further seeds germinated.

Following drilling, three quadrats, each with an area of 0.72m<sup>2</sup>, were fixed in permanent positions along the diagonal axis of each plot. Plants were counted every two to three days in the period up to maximum emergence, thereafter, less frequent assessments were made, but intervals never exceeded 3 weeks. Counting was terminated after the plants had reached growth stage 3,3 (green bud) (Sylvester-Bradley & Makepeace, 1984) and could be expected to contribute to yield.

To assess the effect of cultivation on the seedbed structure, the size distribution of the soil aggregates was measured in three samples (20cm×20cm×5cm deep) taken from each plot immediately after drilling. Each sample was placed in foil trays to preserve its aggregation and transferred to the laboratory. After air drying for 2 months in the laboratory, each sample was passed through a series of square mesh sieves (47mm, 23mm, 11mm, 6.7mm and 3.4mm) taking care to conserve the natural aggregation by avoiding aggressive shaking. Each aggregate fraction was turned out into a separate tray and the stones and straw removed by hand. Each of the fractions was weighed and the proportion (W/W) of each fraction was calculated as the weight of the fraction divided by the total weight of soil in the sample (excluding stones and straw).

Soil moisture in each seedbed was measured twice weekly from drilling to maximum emergence. A steel cylinder with an internal diameter of 7cm was driven 5cm into the soil at five locations along the length of the plot and the enclosed soil removed to a plastic bag. This bulk sample was weighed, transferred to a steel tray and dried to constant weight at 85°C. The stones from the sample were then removed by hand and the dry weight of the soil fraction determined.

Air temperatures, soil temperatures at 2cm depth and rainfall receipts were obtained from the University of Nottingham, Sutton Bonington meteorological site located within 1 km of the field site.

Slug pellets were applied after drilling to the October, November and December sowings for prophylactic control of slugs. Some pigeon grazing was noted during the winter and this was controlled using a gas scarer gun, the level of damage was not considered likely to contribute to seedling fatalities. Grazing by rabbits and game birds was also observed, but was prevented by surrounding the plots with electrified netting.

#### 4.2.2 Stage II

The aim of this second phase of field experimentation was to quantify plant losses during each phase of establishment and attempt to identify which combination of soil physical characteristics and weather conditions influenced seed, seedling and plant losses.

Experiments were conducted at The University of Nottingham Farm between September 1994 and May 1995, in Field 9 (SK 512 266), Dunnington Heath series medium sandy loam and in Field 8 (SK 515 267), Fladbury series non-calcareous alluvial clay. In both fields, the wheat straw from the preceding crop was baled, leaving only stubble.

The addition of the Fladbury series clay provided a direct comparison of soil type under the same weather conditions and was also more representative of soil types in the major rape growing regions. However, cultivations on this heavier soil were only possible during September and October which precluded winter sowings. Up to three seedbed types were compared in this stage; in addition to the Inverted[straw] and Mixed[straw], a Mixed[burnt] seedbed was added using exactly the same cultivations as the Mixed [straw] but without straw and with the stubble burnt off. This allowed a direct comparison of two seedbeds which differed only in respect of cereal residues in the upper profile.

Treatments were replicated three times in a randomised block design. Chopped wheat straw was applied at a rate of  $9 \text{ t ha}^{-1}$  to the Inverted[straw] and Mixed[straw] treatments as in Stage I. Plots were drilled using an Øyvard plot drill, instead of the Nordsten drill used in Stage I, because the more uniform delivery of seed from the drill would assist in seed and seedling recovery in the germination and emergence assessments outlined below.

Each plot ( $4\text{m} \times 13\text{m}$ ) was split into two sections. The first 2m length of each plot was drilled at a higher seed rate ( $400 \text{ viable seeds m}^{-2}$ ) and the remaining area at a rate of  $100 \text{ viable seeds m}^{-2}$ . The high seed rate area was used to assist seed recovery in the germination and emergence assessments; the remaining plot area was used for post emergence plant counts. Plants were counted as in stage I, except that seedlings were also marked with cocktail sticks so that it was possible to identify new seedlings and also which seedlings had been lost.

Total germination was measured after the cessation of emergence in the main plot area by excavating two 30cm rows from the high seed rate area. The number of germinated and ungerminated seeds were counted in each row, extreme diligence ensured that the majority of ungerminated seeds were recovered.

The depth of sowing was assessed by excavating five adjacent rows in the high seed rate area and selecting five seed locations at random in each row. Depth was measured as the

distance from the seedbed surface to the seed, or if the seed had germinated, the distance from the seedbed surface to the margin between the stem and root.

To identify where each cultivation had placed the straw within the soil profile, a 15cm diameter core was extracted from each plot, to a depth of 30cm and split into 5cm layers; the straw was separated from the soil by washing, oven dried at 85°C to constant weight and the distribution by weight calculated for each layer.

The aggregate distribution and soil moisture up to maximum emergence were measured as in Stage I. The results for each stage of the investigation are presented separately.

### 4.3 RESULTS - STAGE I

This section reports the results from the comparison of mixed and inverted seedbeds on emerged seedlings and subsequent survival. Treatments are referred to by seedbed type Inverted[straw], Mixed[straw] and sowing date. A summary of sowing dates is given in Table 4.1.

Table 4.1: Summary of sowing dates and abbreviated reference names

Sowing date	Abbreviated reference
19 October 1993	Oct 93
3 November 1993	ENov 93
19 November 1993	LNov 93
17 December 1993	Dec 93
18 January 1994	Jan 94
21 February 1994	Feb 94
21 March 1994	Mar 94
20 April 1994	Apr 94
19 May 1994	May 94
20 June 1994	June 94
20 July 1994	July 94

#### 4.3.1 Weather

Mean daily dry bulb temperatures ranged from -3 to 26°C over the experimental period (Figure 4.1). Between October and February, large daily temperatures changes were experienced. Emerged seedlings from the Oct 93 - Dec 93 sowings were all exposed to the freezing temperatures in February.



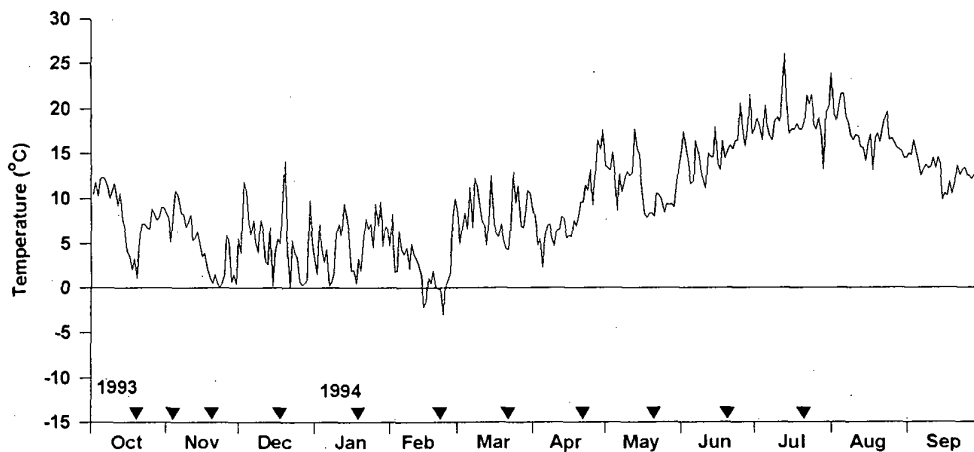


Figure 4.1: Mean daily dry bulb temperatures between October 1993 and September 1994 (Stage I).

Symbols (▼) indicate sowing dates.

Monthly rainfall over the experimental period ranged from 94mm in December 1993 to 8mm in June 1994 (Table 4.2). October, December and January, in particular, were wetter than the long term average while June and July were notably drier.

Table 4.2: Monthly rainfall between October 1993 and August 1994 (Stage I).

		Rainfall (mm)	Long term Average (1916-1996)
1993	October	87	52
	November	57	58
	December	94	55
1994	January	76	53
	February	47	41
	March	64	45
	April	32	40
	May	54	47
	June	8	47
	July	28	50
	August	36	59

### 4.3.2 Seedbed characteristics

#### 4.3.2.1 Soil moisture

Measurements of soil moisture from each sowing date were concatenated to show the pattern of seedbed moisture over the entire experimental period (Figure 4.2). The soil moisture equivalents to field capacity (-0.01 MPa) and permanent wilting point (-1.5 MPa) determined from the water release curves (Section 3.2) are shown. At a given sample date, the Mixed[straw] in most cases had soil moistures 5-10 percentage points higher than the Inverted[straw]. From mid-November to February the Mixed[straw] treatment was above field capacity and reached a peak in January with a soil moisture of 42%, double the threshold value for field capacity. Over this same period, the Inverted[straw] treatment did exceed field capacity but by a smaller margin and had a maximum value of 32%.

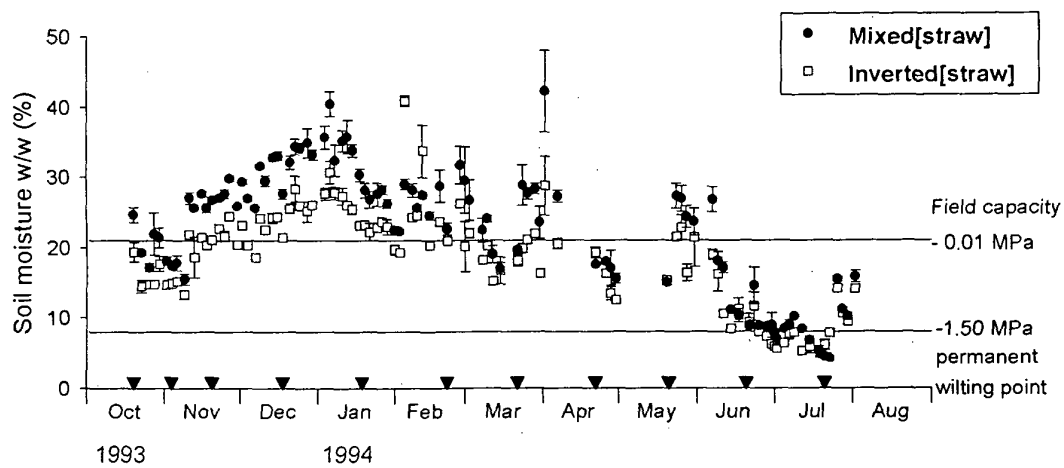


Figure 4.2: Soil moisture (%) in the Mixed[straw] and Inverted[straw] seedbeds during Stage I on Dunnington Heath series sandy loam [Field 2, The University of Nottingham Farm].

The lines indicate field capacity and permanent wilting point calculated from the water release curves described in Section 3.2. Symbols (▼) indicate sowing dates.

#### 4.3.2.2 Soil temperature

Soil temperatures at 2cm depth from the Sutton Bonington meteorological site show the temperature during emergence (Figure 4.3). Cold conditions, close to freezing, were experienced after the Nov 93, Dec 93 and Jan 94 sowings.

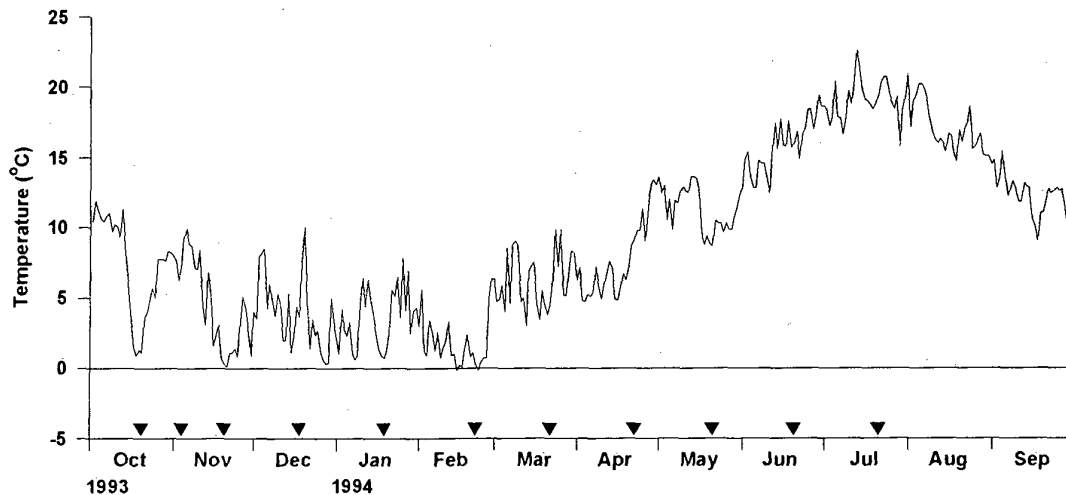


Figure 4.3: Soil temperature 2cm below ground level between October 1993 and September 1994 (Stage I).

Symbols (▼) indicate sowing dates.

#### 4.3.2.3 Aggregate size distribution

To identify differences in the seedbed structure, the largest (>23mm) and smallest (<3.4mm) aggregate size fractions were compared at sowing, for each seedbed type (Figure 4.4). Overall, the proportion of large aggregates over 23mm was never greater than 35% of the total but large variations between sowing dates were evident. Between the Oct 93 and Feb 94 sowings there was no distinct pattern but between Feb 94 and June 94, the proportion of large aggregates fell with each successive sowing. Within sowing dates, differences between seedbed types were generally less than 10 percentage points and only in the Oct 93 and Jan 94 sowings did the Mixed[straw] treatment have significantly ( $P<0.05$ ) more large aggregates. The aggregates <3.4mm generally showed an opposite trend to the larger aggregates (>23mm). Consequently, between Feb 94 and June 94 sowings the proportion increased with each sowing but differences between seedbed types were small and only statistically significant ( $P<0.05$ ) in the Oct 93 and July 94 sowings.

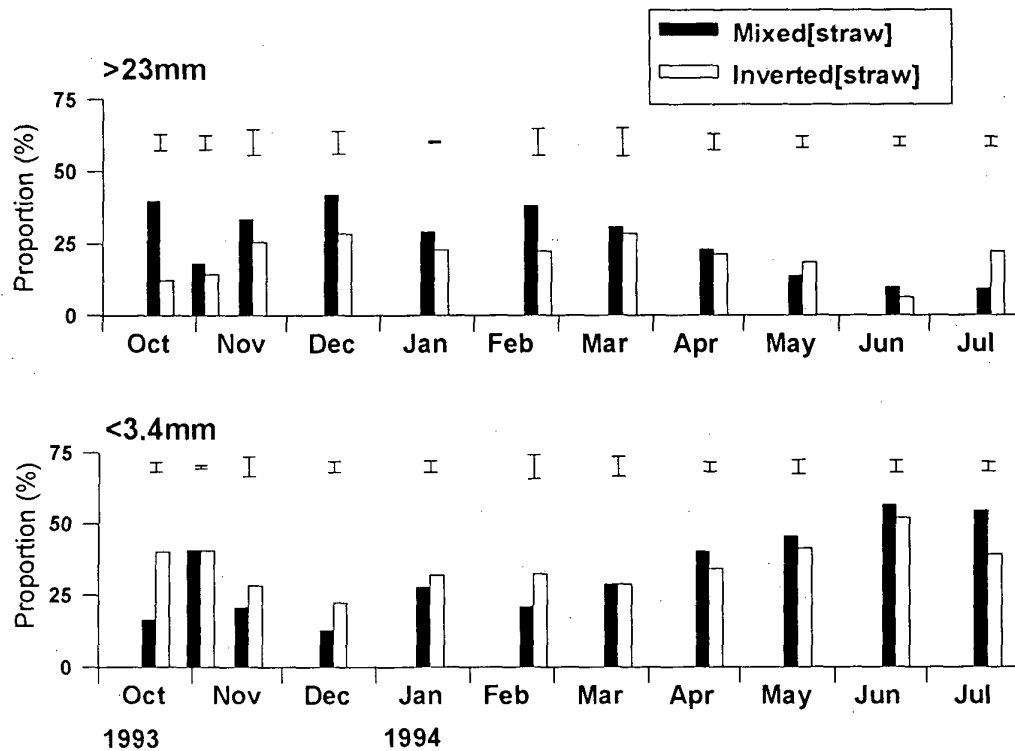


Figure 4.4: Proportion of aggregates >23mm and <3.4mm in the Mixed[straw] and Inverted[straw] seedbeds on Dunnington Heath series sandy loam [Field 2, The University of Nottingham Farm] during Stage I. Error bars indicate SEDs (5df) calculated for each individual sowing date/aggregate size combination.

### 4.3.3 Plant populations

In order to compare between sowing dates, the data are presented in four sections:

1. Sowing to maximum population
2. Maximum populations
3. Plant losses after maximum population
4. Final established populations

To provide an overview of all these stages (from sowing to final establishment) the plant populations are presented for each sowing date (Figure 4.5).

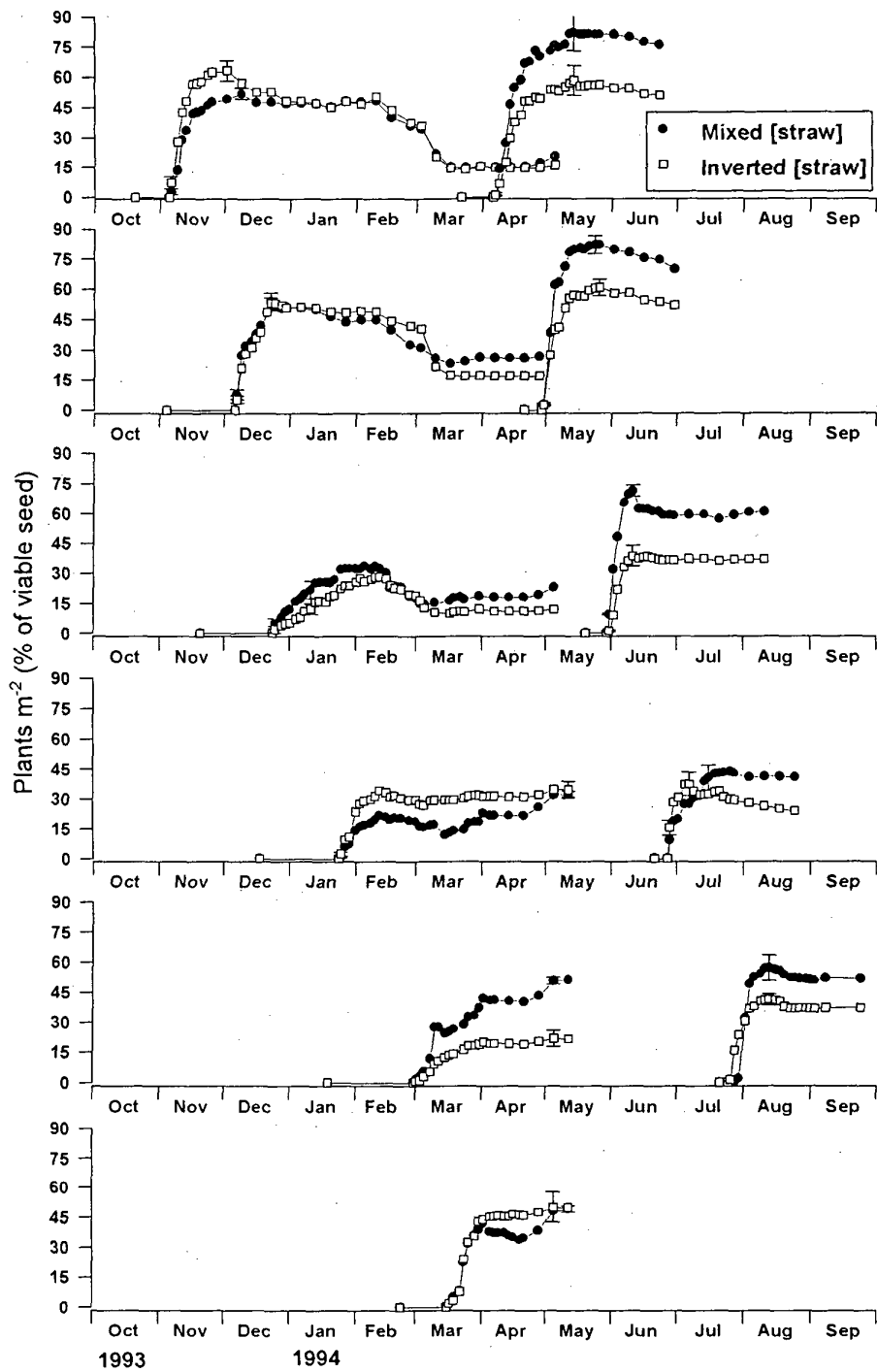


Figure 4.5: Plant numbers m<sup>-2</sup> (% of viable seeds) from the eleven sequential sowings on Dunnington Heath series sandy loam [Field 2, The University of Nottingham Farm]. Error bars indicate positive and negative s.e. (2df) for maximum populations.

#### 4.3.3.1 Sowing to maximum population

The time lag between drilling and first emergence increased with each successive sowing up till the Jan 94 sowing (in which the first seedlings took six weeks to emerge) and thereafter shortened to less than seven days in the July sowing. To examine the relationship between temperature and emergence, the thermal time (sum of daily soil temperatures  $>0^{\circ}\text{C}$  at 2cm depth) was calculated for the periods between the date of drilling and 50% emergence. Over the eleven sowing dates, the average thermal time to 50% emergence was  $173 \pm 8.6^{\circ}\text{C d}$  in the Mixed[straw] and  $165 \pm 3.6^{\circ}\text{C d}$  in the Inverted[straw] (Table 4.3). The Mixed[straw] included two outlying values from the June 94 and July 94 sowings, excluding these reduced the average for this seedbed to  $161 \pm 1.4^{\circ}\text{C d}$  and reduced the total variation between individual values to less than  $30^{\circ}\text{C d}$ .

Table 4.3: Thermal time ( $^{\circ}\text{C d}$  above  $0^{\circ}\text{C}$  from soil temperature at 2cm depth) to 50% emergence from the 11 sowing dates in Mixed[straw] and Inverted[straw] seedbeds on the Dunnington Heath series sandy loam [Field 2, The University of Nottingham Farm].

Sowing date	Estimated date at 50% of maximum emergence		Thermal time between sowing and 50% emergence ( $^{\circ}\text{C d}$ )	
	Mixed	Inverted	Mixed	Inverted
19 Oct 1993	10 Nov 93	9 Nov 93	160	151
3 Nov 1993	8 Dec 93	10 Dec 93	166	176
19 Nov 1993	5 Jan 94	11 Jan 94	161	179
17 Dec 1994	2 Feb 94	30 Jan 94	165	155
18 Jan 1994	8 Mar 94	11 Mar 94	161	179
21 Feb 1994	23 Mar 94	23 Mar 94	155	155
21 Mar 1994	13 Apr 94	13 Apr 94	155	155
20 Apr 1994	3 May 94	3 May 94	157	157
19 May 1994	2 June 94	3 June 94	165	179
20 June 1994	2 July 94	28 June 94	*229	156
20 July 1994	31 July 94	28 July 94	*232	173
Mean $\pm$ s.e.			$173 \pm 8.6$	$165 \pm 3.6$
Mean excluding June* and July* $\pm$ s.e.			$161 \pm 1.4$	

#### 4.3.3.2 Maximum populations

Over the 11 sowings, the Mixed[straw] treatment produced, on average, a maximum population of 55 plants m<sup>-2</sup> (per 100 viable seeds sown) compared to 44 in the Inverted[straw] (Table 4.4). However, there was a significant (P<0.01) interaction between seedbed type and sowing date. In nine out of eleven sowings, the Mixed[straw] seedbed produced higher maximum plant populations than the Inverted[straw] and in many cases this was significantly higher; the Inverted[straw] seedbed only produced more seedlings than the Mixed[straw] seedbed in the Oct 93 sowing. The highest populations were produced from the Mar 94 and Apr 94 sowings in the Mixed[straw] seedbed (82 plants m<sup>-2</sup> per 100 viable seeds) and from the Oct 93 and Apr 94 sowings in the Inverted[straw] with 63 and 61 plants m<sup>-2</sup> respectively. The lowest populations resulted from the Dec 93 sowing in the Mixed[straw] and from the Jan 94 sowing in the Inverted[straw] with 32 and 22 plants m<sup>-2</sup> respectively.

Averaging across both seedbed types and sowing dates, the data show that almost half the viable seeds drilled either failed to produce an emerged seedling or had died prior to the maximum population being recorded.

Table 4.4: Maximum plant populations, expressed as a percentage of 200 viable seed sown m<sup>-2</sup>, from 11 sowing dates in Mixed[straw] and Inverted[straw] seedbeds on the Dunnington Heath series sandy loam [Field 2, The University of Nottingham Farm].

Sowing date	Mixed[straw]	Inverted[straw]
Oct 93	52	63
ENov 93	54	53
LNov 93	34	28
Dec 93	32	35
Jan 94	51	22
Feb 94	50	50
Mar 94	82	58
Apr 94	82	61
May 94	71	39
June 94	44	37
July 94	57	41
Mean	55	44

Analysis of variance	df	Prob	SED
Seedbed	1	<0.01	2.1
Sowing date	10	<0.01	4.9
Seedbed.sowdate	10	<0.01	6.9
Residual	42		

#### 4.3.3.3 Plant losses after maximum population

Plant losses could be grouped into three broad categories according to sowing date: autumn sowings (Oct 93, ENov 93 and LNov 93), winter sowings (Dec 93, Jan 94 and Feb 94) and spring/summer sowings (Mar 94, Apr 94, May 94, June 94 and July 94) (Table 4.5). The autumn sowings lost most plants, both in terms of losses from 100 viable seeds sown and as a proportion of the maximum plant population. The highest losses were in the Oct 93 Inverted[straw] seedbed in which three quarters of the maximum population failed to establish. Fewer plants were lost in the successive ENov 93 and LNov 93 sowings but the proportion lost was always greater than 30% of maximum populations. Within each of the three autumn sowings, proportionally more plants survived in the Mixed[straw] treatment.

No losses were recorded in the winter sowings, primarily due to the protracted emergence period which often resulted in post emergence losses being masked by newly emerging seedlings. In the spring/summer sowings, emergence was rapid and losses were generally lower than in the autumn sowings, with the exception of the June 94 Inverted[straw] where 36% of plants present at maximum population were subsequently lost, compared to only 6% in the Mixed[straw] seedbed.

Table 4.5: Losses in the period after maximum emergence to final establishment from 11 sowing dates in Mixed[straw] and Inverted[straw] seedbeds on the Dunnington Heath series sandy loam [Field 2, The University of Nottingham Farm].

Dashes indicate that no losses were recorded after maximum emergence.

Sowing date	losses (plants m <sup>-2</sup> out of 100 viable seeds sown)		Losses as a proportion of the maximum population	
	Mixed[straw]	Inverted[straw]	Mixed[straw]	Inverted[straw]
Oct 93	31	47	60	75
ENov 93	27	36	50	68
LNov 93	11	16	32	58
Dec 93	-	-	-	-
Jan 94	-	-	-	-
Feb 94	-	-	-	-
Mar 94	6	7	7	12
Apr 94	12	9	15	14
May 94	10	2	15	4
June 94	3	14	6	36
July 94	8	7	15	16
Mean	14	17	14	26



#### 4.3.3.4 Final established populations

Over the eleven sowings, the Mixed[straw] seedbeds produced significantly more established plants than the Inverted[straw] seedbeds (Table 4.6). Final plant populations ranged from 20 to 76 m<sup>-2</sup> in the Mixed[straw] and from 12 to 52 m<sup>-2</sup> in the Inverted[straw]. There was a significant (P<0.05) interaction between seedbed type and sowing date. The Inverted[straw] seedbed never had higher established plant populations than the Mixed[straw] and the Mixed[straw] produced significantly (P<0.05) more established plants than the Inverted[straw] in the Jan 94 and Mar 94 - Jul 94 sowings. The highest final populations, in both seedbeds, were from the Mar 94 and Apr 94 sowings.

Table 4.6: Final establishment as a percentage of viable seeds sown, from 11 sowing dates in Mixed[straw] and Inverted[straw] seedbeds on the Dunnington Heath series sandy loam [Field 2, The University of Nottingham Farm].

Sowing date	Mixed[straw]	Inverted[straw]
Oct 93	20	16
ENov 93	28	17
LNov 93	23	12
Dec 93	32	35
Jan 94	51	22
Feb 94	49	50
Mar 94	76	51
Apr 94	70	52
May 94	60	37
June 94	41	24
July 94	49	34
Mean	46	32

Analysis of variance	df	Prob	SED
Seedbed	1	<0.01	2.0
Sowing date	10	<0.01	4.6
Seedbed.sowdate	10	0.02	6.5
Residual	42		

Stage I investigated post emergence losses over a range of weather conditions. In stage II, germination and total emergence was also recorded to provide an analysis of losses in every phase of the establishment process. A Mixed[burnt] seedbed was introduced to provide a comparison with the Mixed[straw] seedbed in order to assess the effects of straw and autumn sowings were made on an alluvial clay, as well as the sandy loam, to give a contrast in soil type.

## 4.4 RESULTS - STAGE II

A total of eight sowings were made, but only the early September (ESept 94), late September (LSept 94) and October (Oct 94) sowings included a full comparison of the Mixed[straw], Mixed[burnt] and Inverted[straw] seedbed on both soil types (Table 4.7). The main comparisons and analysis was therefore restricted to these three autumn sowing dates, but data from the other sowings on the Dunnington Heath sandy loam are presented where appropriate.

Table 4.7: Summary of sowing dates, soil and seedbed treatment combinations tested during Stage II of the sequential sowing experiments.

Sowing date	Reference	Dunnington Heath sandy loam	Fladbury non-calcareous clay
6 September 1994	ESept 94	Mixed[straw] Mixed[burnt] Inverted[straw]	
28 September 1994	LSept 94	Mixed[straw] Mixed[burnt] Inverted[straw]	
27 October 1994	Oct 94	Mixed[straw] Mixed[burnt] Inverted[straw]	
24 November 1994	Nov 94	Mixed[straw]	-
21 December 1994	Dec 94	Mixed[straw]	-
28 February 1995	Feb 95	Mixed[straw] Mixed[burnt] Inverted[straw]	-
20 March 1995	Mar 95	Mixed[straw]	-
1 May 1995	May 95	Mixed[straw]	-

### 4.4.1 Weather

Dry bulb temperatures ranged from -4 to 27°C between September 1994 and July 1995 (Figure 4.6). Between September 1994 and the end of November 1994 the average daily temperature never fell below 4.5°C. During December 1994 and January 1995, large temperature variations of +14 to -4°C were recorded.

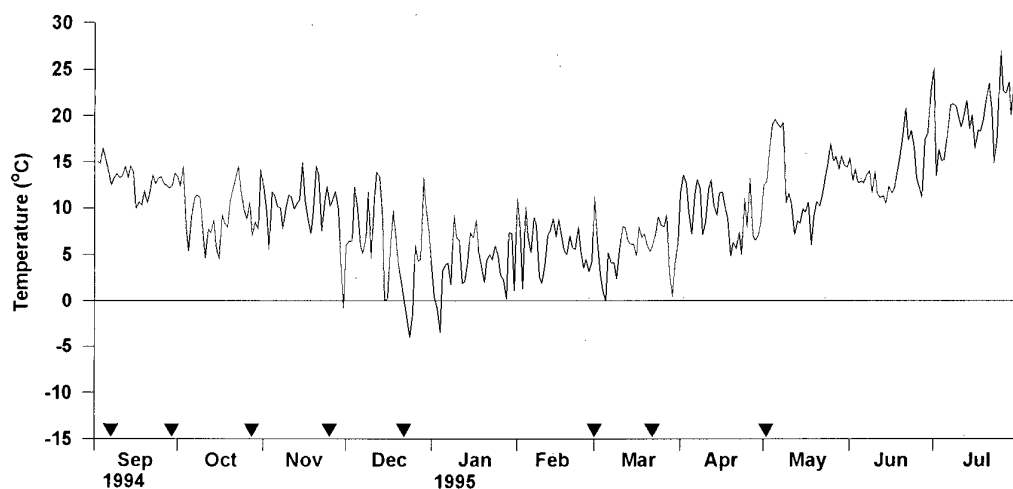


Figure 4.6: Mean daily dry bulb temperature between September 1994 and Jul 1995 (Stage II). Symbols (▼) indicate sowing dates.

Monthly rainfall over the experimental period ranged from 105mm in September 1994 to 11mm in July 1995 (Table 4.2). September, December and January were almost twice as wet as the long term average. However, from March to July rainfall was always below the long term average and the combined deficit, compared to the long term average, over this period was 135mm.

Table 4.8: Monthly rainfall between September 1994 and Jul 1995 (Stage II).

Year	Month	Rainfall (mm)	Long term Average (1916-1996)
1994	August	36	59
	September	105	57
	October	44	52
	November	67	58
	December	94	55
1995	January	105	53
	February	55	41
	March	35	45
	April	13	40
	May	23	47
	June	12	47
	July	11	50

#### **4.4.2 Soil physical characteristics**

The results from the soil moisture, aggregate size distribution, straw position and depth of sowing measurements are presented to show the difference in seedbed structure produced by each cultivation method at each sowing on the two soil types.

##### *4.4.2.1 Soil moisture*

Irrespective of soil type, the Mixed[straw] seedbeds were always wetter than the Mixed[burnt] (Figure 4.7 and Figure 4.8). Within each soil type there was no discernible difference between soil moisture contents of the Mixed[burnt] or Inverted[straw] seedbeds.

On the Dunnington Heath sandy loam, the higher moisture content associated with the Mixed[straw] seedbed resulted in the seedbed being above field capacity during December, January and periods in March, whereas, in the other seedbeds on this soil, the moisture contents was always within the optimal range of -0.01 MPa and -1.5 MPa.

Overall, soil moistures were higher on the Fladbury series clay. During September, soil moisture in the Mixed[burnt] and Inverted[straw] remained within the optimum range but in the Mixed[straw] it increased above field capacity on two sample occasions. Between November and March all seedbed types had moisture contents in excess of field capacity and this was exacerbated by the presence of straw in the surface profile.

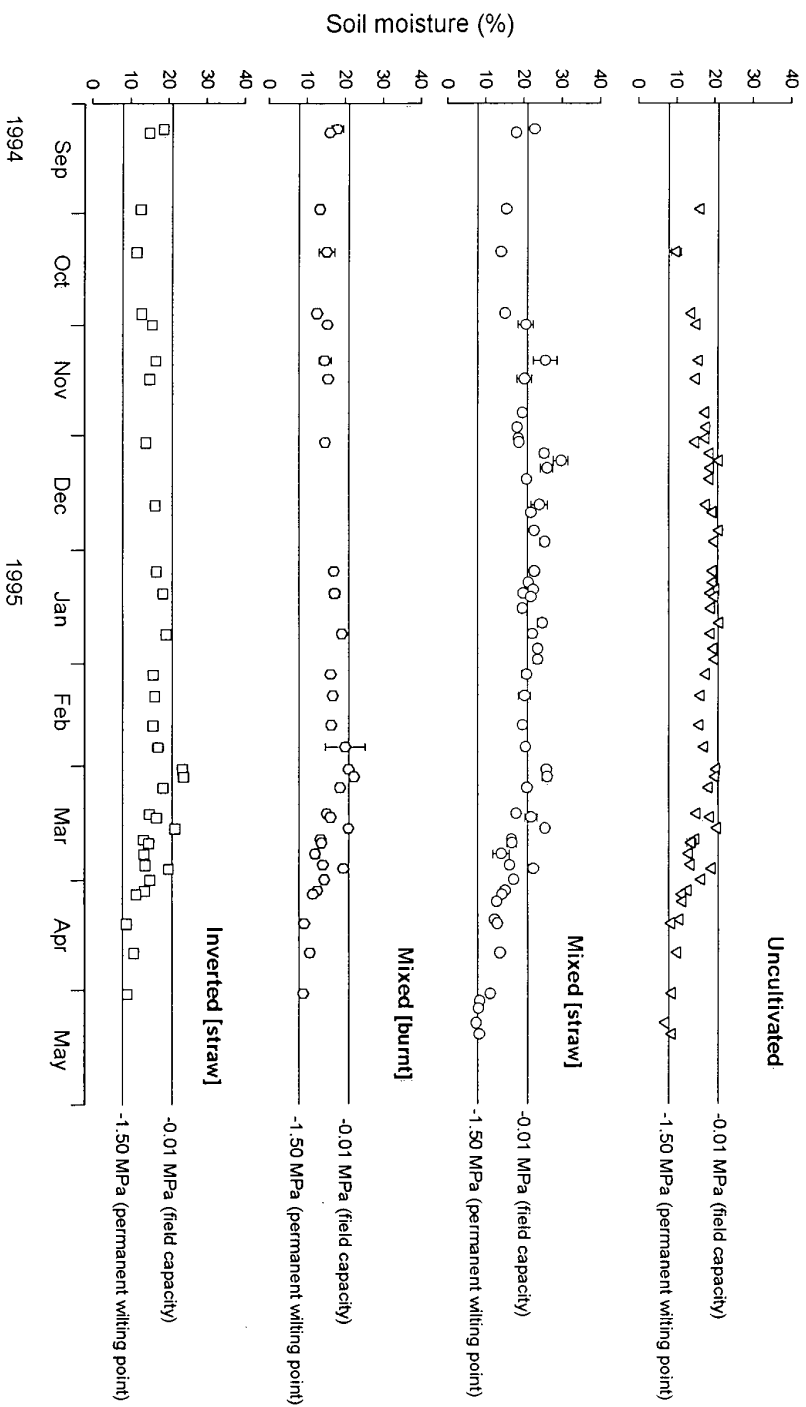


Figure 4.7: Soil moisture (%) in the top 5cm of the seedbed profile in Uncultivated, Mixed[straw], Mixed[burnt] and Inverted[straw] treatments on the Dunnington Heath sandy loam [Field 9, The University of Nottingham Farm]. Error bars indicate double standard errors.

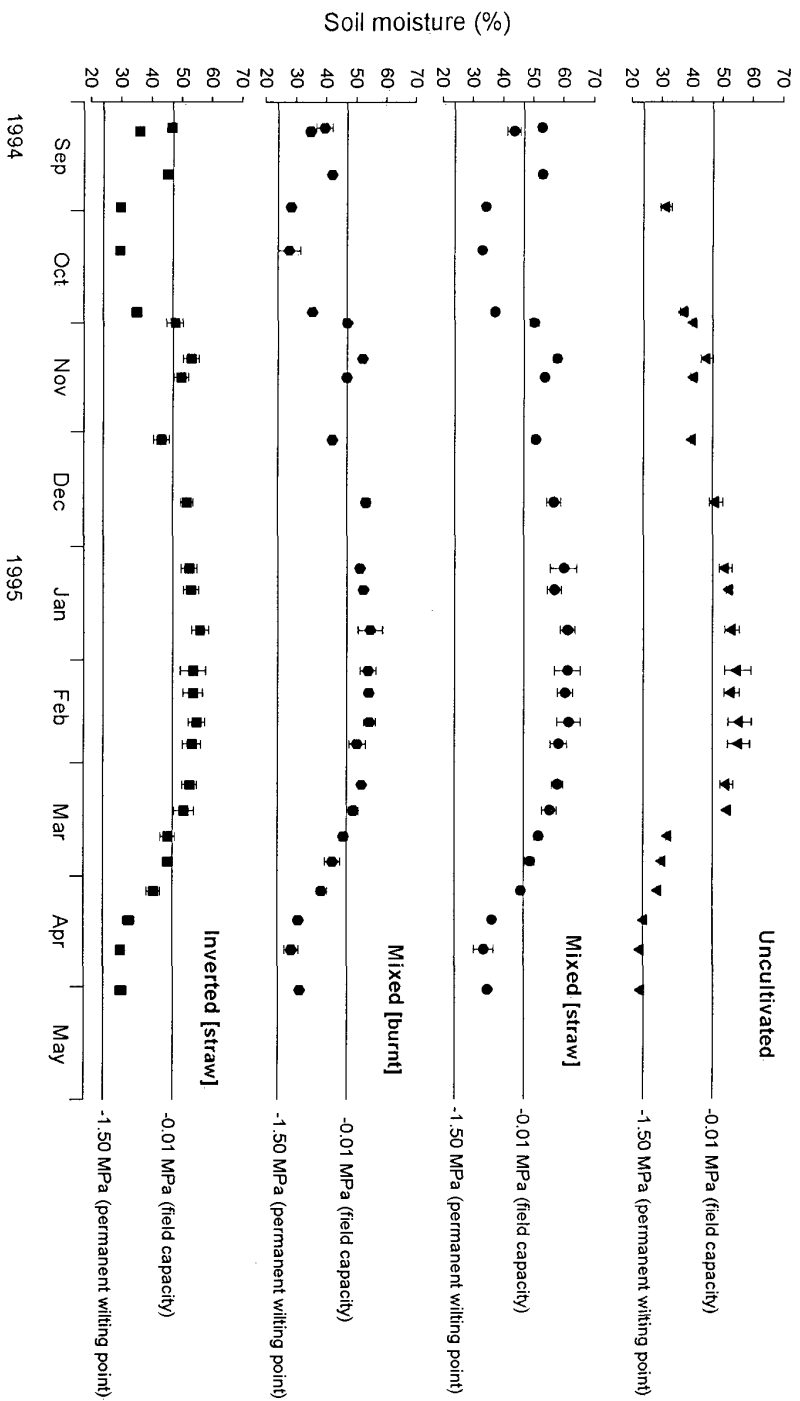


Figure 4.8: Soil moisture (%) in the top 5cm of the seedbed profile in Uncultivated, Mixed[straw], Mixed[burnt] and Inverted[straw] treatments on the Fladbury series clay [Field 8, The University of Nottingham Farm]. Error bars indicate double standard errors.

#### 4.4.2.2 Soil temperature

Soil temperatures at 2cm depth during autumn sowings never fell below 5°C, but freezing conditions followed the Dec 94 sowing (Figure 4.9).

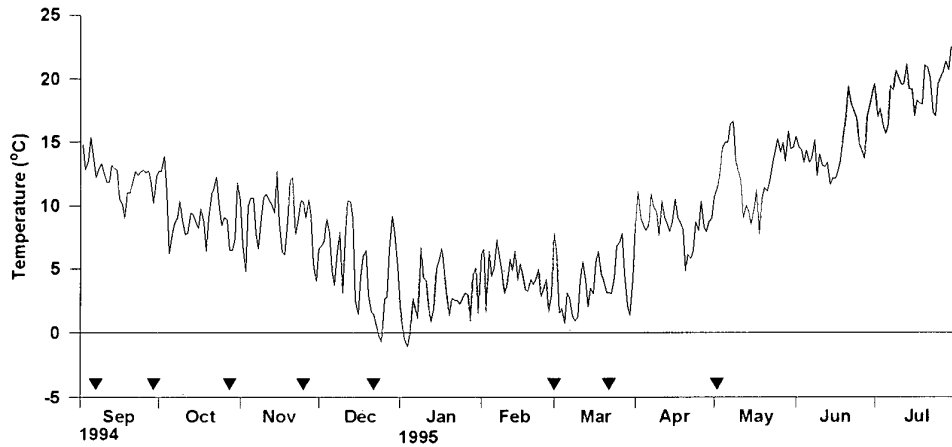


Figure 4.9: Soil temperature at 2cm depth between September 1994 and July 1995 (Stage II). Symbols (▼) indicate sowing dates.

#### 4.4.2.3 Aggregate size distribution

In the ESept 94, LSept 94 and Oct 94 sowings all three seedbeds types on the Fladbury clay had a greater proportion of large aggregates over 23mm and fewer small aggregates <3.4mm compared with the same seedbed type on the Dunnington Heath sandy loam (Figure 4.10). On the Dunnington Heath sandy loam, cultivations significantly ( $P<0.001$ ) reduced the proportion of large aggregates and increased the proportion of small aggregates compared to uncultivated soil. In general, the magnitude of these effects was greater in the Mixed seedbeds compared to the Inverted.

On the Fladbury clay, cultivations tended to have the opposite effect, producing more aggregates >23mm and decreasing the proportion of small aggregates <3.4mm. Mixing had relatively smaller effects than inversion which significantly increased the proportion of large and reduced the proportion of small aggregates in both the ESept 94 and LSept 94 sowings; however, in the Oct 94 sowing, inversion had no significant effect on either aggregate fraction.

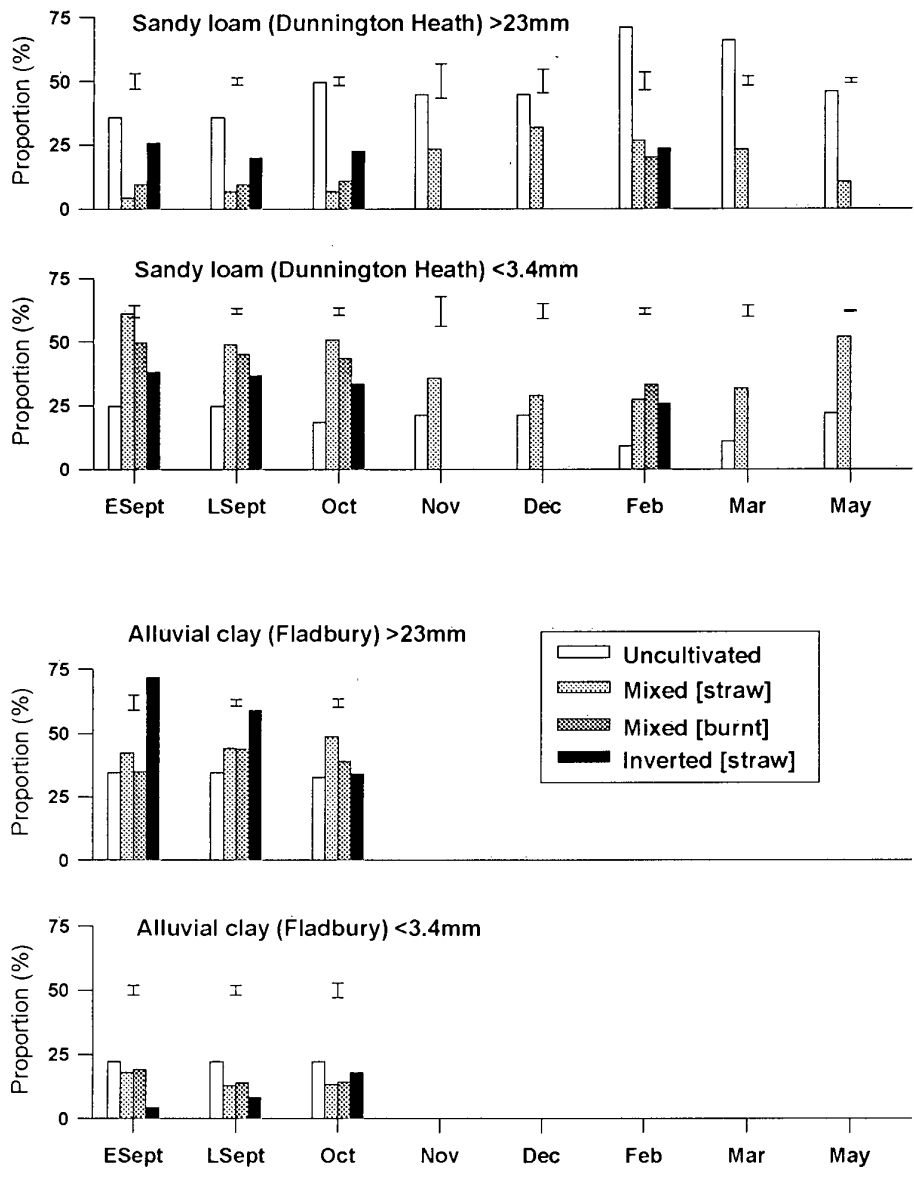


Figure 4.10: Aggregate size distribution (proportion by weight) from uncultivated, Mixed[straw], Mixed[burnt] and Inverted[straw] seedbeds on the Dunnington Heath series sandy loam and the Fladbury series clay [Field 9 and Field 8, The University of Nottingham Farm, respectively]. Error bars indicate SEDs (6df for ESept 94, LSept 94, Oct 94 and Feb 95 sowings; 2df for Nov 94, Dec 94, Mar 95 and May 95 sowings).



#### 4.4.2.4 *Straw position*

A principal reason for using Mixed and Inverted seedbeds was to investigate how straw position in the seedbed was related to the establishment process. The Mixed[*straw*] and Inverted[*straw*] produced distinct distributions of straw down the soil profile (Figure 4.11 and Figure 4.12). In every sowing on the Dunnington Heath sandy loam, the straw in the Mixed[*straw*] treatment was concentrated near the surface and in the 0-5cm layer of the soil, compared to the Inverted[*straw*] where the majority was below 10cm. On the Fladbury clay, the same general pattern was observed in the Mixed[*straw*] but the distribution of straw down the 30cm profile of the Inverted[*straw*] treatment was more uniform.

To provide a quantitative comparison of straw in the top 5cm of the profile, the proportions of straw, by weight, on the surface and 0-5cm layers were combined. Over the four sowings where seedbed comparisons were made, the proportion of straw recovered from this upper horizon was significantly ( $P < 0.001$ ) greater in the mixed straw treatment 69.0% (s.e. 6.2) compared to the inverted 9.8% (s.e. 3.2). From the 900g straw  $m^{-2}$  applied this equated to 621g (s.e. 55.8) in the top 5cm of the Mixed[*straw*] seedbeds compared with 88.2 g (s.e. 28.8.) in the Inverted[*straw*].

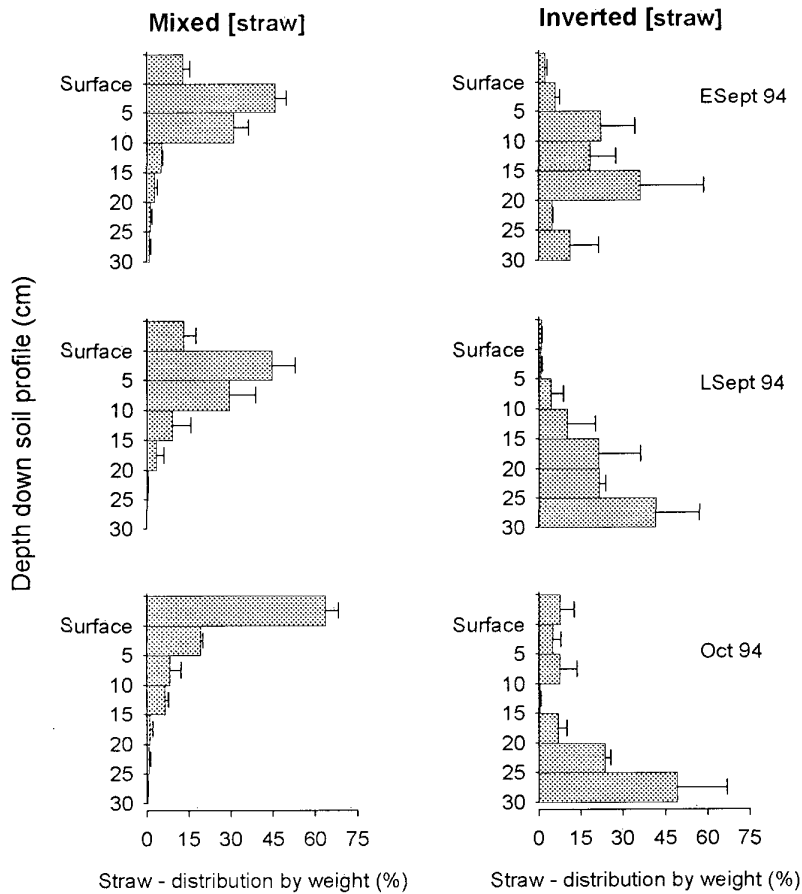


Figure 4.11: Distribution of straw (by weight) on the surface and in 5cm increments down the soil profile (to 30cm) in the Mixed[straw] and Inverted[straw] seedbeds on the Dunnington Heath series sandy loam [Field 9, The University of Nottingham Farm]. Error bars indicate single standard errors.

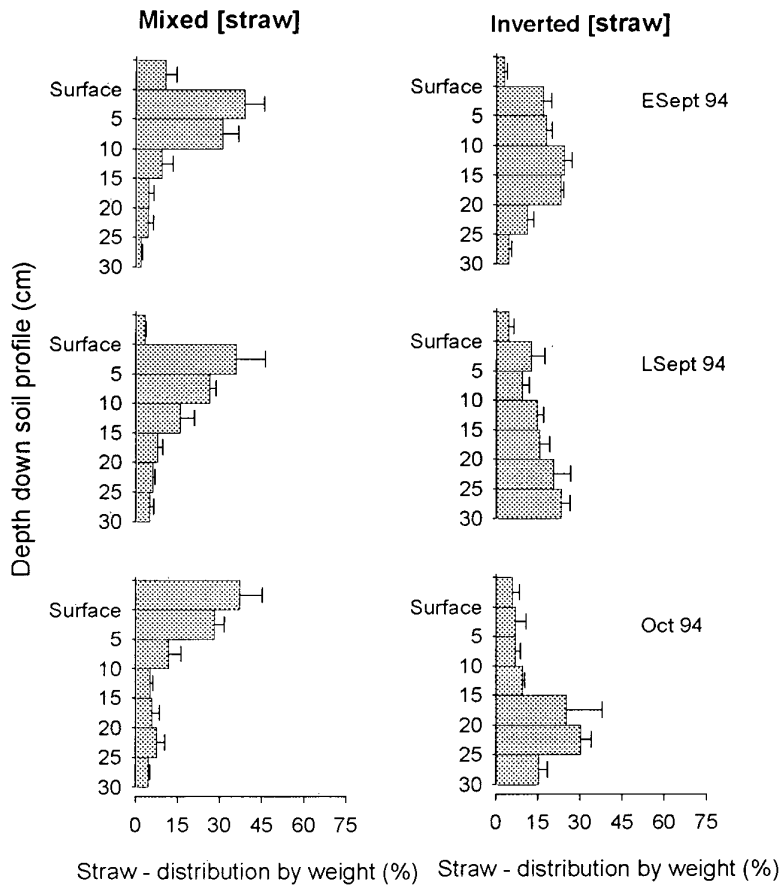


Figure 4.12: Distribution of straw (by weight) on the surface and in 5cm increments down the soil profile (to 30cm) on in the Mixed[straw] and Inverted[straw] seedbeds on the Fladbury series clay [Field 8, The University of Nottingham Farm]. Error bars indicate single standard errors.

#### 4.4.2.5 Depth of sowing

The depth of sowing in the ESept 94, LSept 94 and Oct 94 sowings ranged from 0 to 8cm. The frequency distribution varied according to both seedbed and soil type (Figure 4.13 and Figure 4.14).

In the Dunnington Heath sandy loam Mixed[straw] seedbed, seed depth was uniform with most seed between 1-3 cm deep. The Mixed[burnt] ESept 94 was equally uniform but the LSept 94 and Oct 94 sowings had much more variable seed placement, with most below 3cm. The latter pattern was also characteristic of the Inverted[straw] seedbed.

In the Mixed[straw] seedbed on the Fladbury clay, most seed was drilled between 1-3cm with very little below 5cm and none at the surface. On the Mixed[burnt] depth of sowing was less uniform with most seed drilled between 2-6cm, increasing the average sowing depth by 1cm compared to the Mixed[straw] treatment. The average seed depth in the Inverted[straw] treatment was 3.9cm similar to the Mixed[burnt].

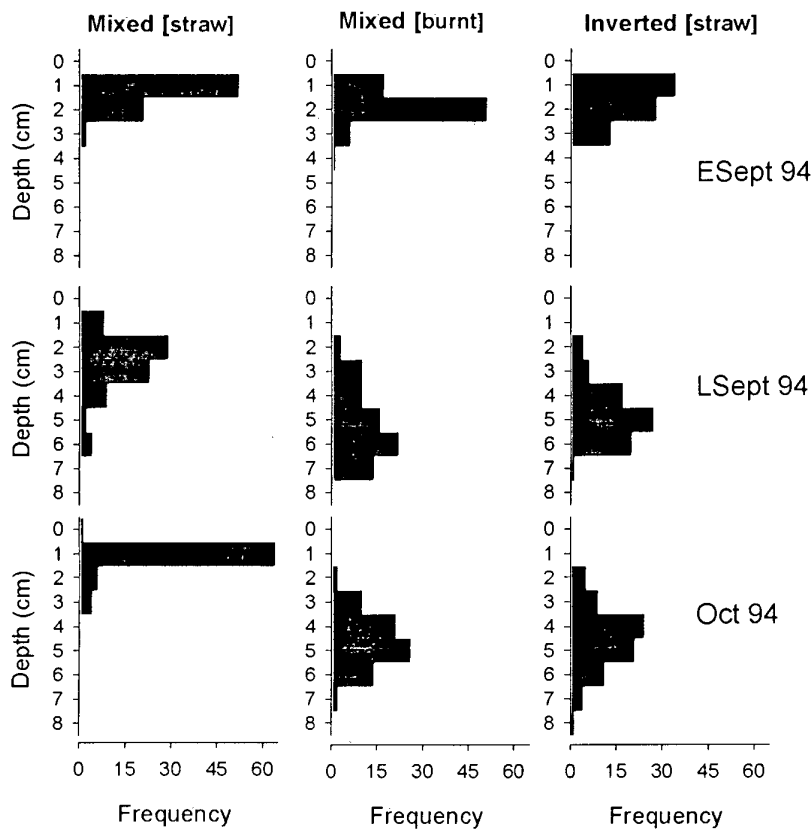


Figure 4.13: Depth of sowing in the three seedbed types in the Mixed[straw], Mixed[burnt] and Inverted[straw] seedbeds on the Dunnington Heath series sandy loam [Field 9, The University of Nottingham Farm].

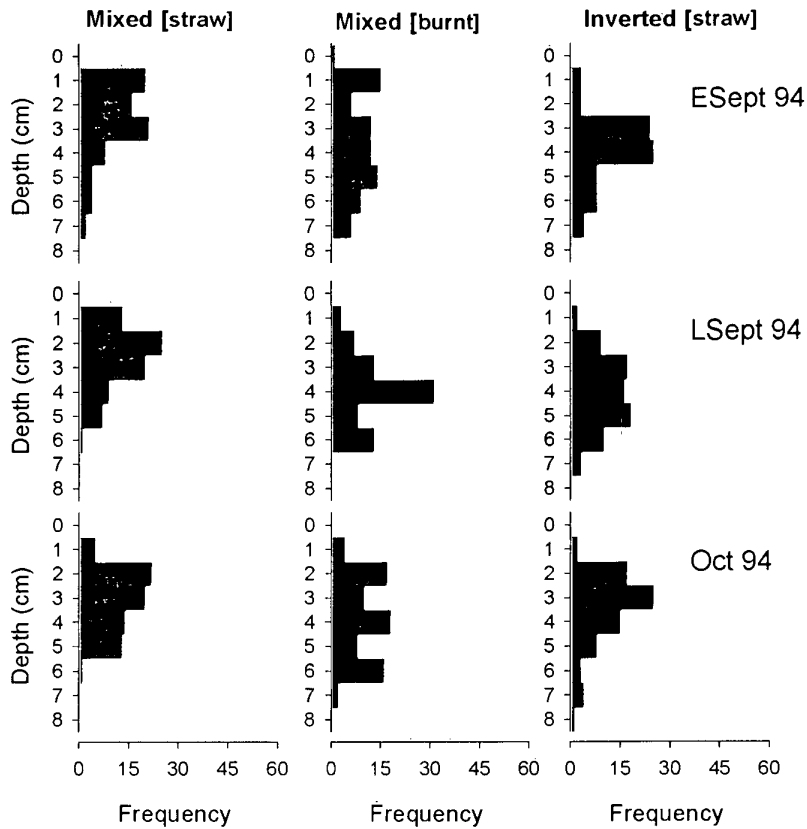


Figure 4.14: Depth of sowing in the three seedbed types in the Mixed[straw], Mixed[burnt] and Inverted[straw] seedbeds on the Fladbury series clay [Field 8, The University of Nottingham Farm].

#### 4.4.3 Germination, emergence and plant populations

The fate of seeds, seedlings and plants from the Stage II sowings are presented in four sections:

1. Germination
2. Emergence
3. Plant populations throughout the season and final establishment
4. Summary of losses in each phase

##### 4.4.3.1 Germination

Germination in the ESept 94, LSept 94 and Oct 94 sowings was high and similar to that in the laboratory (>90%) (Table 4.9) with no significant difference between soil types. Of the

remaining sowings on the Dunnington Heath sandy loam, the Nov 94, Dec 94, Feb 95 and May 95 sowings all showed reduced germination. In the Feb 95 sowing, germination was significantly reduced but there was no significant difference between seedbeds i.e. it was not related to seedbed structure.

Table 4.9: Percentage germination (from viable seed) at each sowing date seedbed combination on the Dunnington Heath Sandy Loam and Fladbury clay.

Sowing date	Dunnington Heath sandy loam			Fladbury clay		
	Mixed [straw]	Mixed [burnt]	Inverted [straw]	Mixed [straw]	Mixed [burnt]	Inverted [straw]
ESept 94	97	99	98	99	98	98
LSept 94	98	99	98	100	99	98
Oct 94	95	97	97	97	96	93
Nov 94	84	-	-	-	-	-
Dec 94	84	-	-	-	-	-
Feb 95	69	72	70	-	-	-
Mar 95	93	-	-	-	-	-
May 95	88	-	-	-	-	-

#### 4.4.3.2 Emergence

The average emergence from 100 viable seeds in the ESept 94, LSept 94 and Oct 94 ranged from 78% to 42% (Table 4.10). The highest average emergence over the three sowings was measured in the Mixed[straw] seedbed on the Dunnington Heath sandy loam and on the Mixed[burnt] on the Fladbury clay. There were significant interactions between soil type and seedbed ( $P < 0.01$ ) and between seedbed and sowing date ( $P < 0.05$ ), indicating that seedbeds had different effects depending on the soil type but that the effect differed between sowing dates.

These data are distinct from previous estimates of emergence, since plants were tagged as they emerged and so all seedlings which achieved two cotyledons were counted even if they died and were 'replaced' by newly emerged seedlings. To determine the extent of plant losses during the period when new seedlings were still emerging, the difference between true emergence and maximum population was calculated (Table 4.11). In most cases the differences were small with little variation between seedbed types i.e. few plants were lost in the period up to maximum emergence, but this was not the case in the ESept 94 sowing on the Fladbury series clay where up to 16 plants  $m^{-2}$  were lost, suggesting that in some cases, maximum populations were an underestimate of true emergence.

Table 4.10: Percentage emergence from viable seed in the ESept 94, LSept 94 and Oct 94 sowings on the Dunnington Heath Sandy Loam and the Fladbury clay [Field 9 and Field 8, The University of Nottingham Farm].

Sowing date	Dunnington Heath sandy loam			Fladbury clay		
	Mixed [straw]	Mixed [burnt]	Inverted [straw]	Mixed [straw]	Mixed [burnt]	Inverted [straw]
ESept 94	66	59	70	67	66	71
LSept 94	78	50	55	65	65	45
Oct 94	77	59	57	42	74	63
Mean	74	56	61	58	68	60

Analysis of variance	df	Prob	SED
Soiltype	34	NS	3.7
Seedbed	34	NS	3.0
Sowingdate	34	NS	3.7
Soiltype . Seedbed	34	<0.01	5.2
Soiltype . Sowingdate	34	NS	5.2
Seedbed . Sowingdate	34	<0.05	6.3
Soiltype . Seedbed . Sowingdate	34	NS	9.0

Table 4.11: Difference between total emergence and maximum population for the ESept 94, LSept 94 and Oct 94 sowings on the Dunnington Heath sandy loam and the Fladbury clay [Field 9 and Field 8, The University of Nottingham Farm].

Sowing date	Treatment	Dunnington Heath sandy loam			Fladbury clay		
		Total emergence	Max. population	Difference (% points)	Total emergence	Max. population	Difference (% points)
ESept 94	Mixed[straw]	66	63	3	67	57	10
	Mixed[burnt]	59	56	3	66	51	15
	Inverted[straw]	70	65	5	71	55	16
LSept 94	Mixed[straw]	78	76	2	65	59	6
	Mixed[burnt]	50	47	3	65	61	4
	Inverted[straw]	55	51	4	45	40	5
Oct 94	Mixed[straw]	77	75	2	42	37	5
	Mixed[burnt]	59	55	4	74	68	6
	Inverted[straw]	57	55	2	63	57	6

The thermal time to 50% of total emergence was calculated to provide a comparison with estimates in Stage I based on time to maximum population (Table 4.12 and Table 4.13). The average over the ESept 94, LSept 94 and Oct 94 sowings was 160 °C d (s.e. 1.9) on the Dunnington Heath series sandy loam and 160 °C d (s.e. 1.6) on the Fladbury clay. Of the remaining sowings on the Dunnington Heath sandy loam, the Feb 95 and May 95 sowings fell outside the normal range indicating that in these sowings the period up to emergence was limited by another factor.

Table 4.12: Thermal time (°C d above 0°C from soil temperature at 2cm depth) to 50% emergence from sowings in Mixed[straw], Mixed[burnt] and Inverted[straw] seedbeds on the Dunnington Heath series sandy loam [Field 9, The University of Nottingham Farm].

Sowing date	Estimated date at			Thermal time		
	50% of maximum emergence			sowing to 50% emergence (°C d)		
	Mixed [straw]	Mixed [burnt]	Inverted [straw]	Mixed [straw]	Mixed [burnt]	Inverted [straw]
6 Sept 1994	19 Sept	19 Sept	19 Sept	165	165	165
28 Sept 1994	14 Oct	15 Oct	15 Oct	154	162	162
27 Oct 1994	12 Nov	13 Nov	12 Nov	151	161	151
24 Nov 1994	16 Dec	-	-	157	-	-
21 Dec 1994	6 Feb	-	-	159	-	-
28 Feb 1995	6 Apr	6 Apr	6 Apr	182	182	182
20 Mar 1995	12 Apr	-	-	167	-	-
1 May 1995	25 May	-	-	306	-	-

Table 4.13: Thermal time (°C d above 0°C) from soil temperature at 2cm depth) to 50% emergence from sowings in Mixed[straw], Mixed[burnt] and Inverted[straw] seedbeds on the Fladbury series clay [Field 8, The University of Nottingham Farm].

Sowing date	Estimated date at			Thermal time between		
	50% of maximum emergence			sowing and 50% emergence (°C d)		
	Mixed [straw]	Mixed [burnt]	Inverted [straw]	Mixed [straw]	Mixed [burnt]	Inverted [straw]
6 Sept 1994	19 Sept	19 Sept	19 Sept	165	165	165
28 Sept 1994	14 Oct	14 Oct	14 Oct	154	154	154
27 Oct 1994	13 Nov	13 Nov	13 Nov	161	161	161



Using the equation derived for emergence in relation to sowing depth (Section 3.7), a predicted emergence was calculated from the sowing depth data. This was then deducted from the recorded values of seedling emergence to give the number of seeds (out of 100) whose failure could not be explained by sowing depth (Table 4.14). There was no distinct pattern between seedbed types.

Table 4.14: Unemerged seedlings (out of 100 viable seeds) NOT accounted for by drilling depth.

Sowing date	Dunnington Heath sandy loam			Fladbury clay		
	Mixed [straw]	Mixed [burnt]	Inverted [straw]	Mixed [straw]	Mixed [burnt]	Inverted [straw]
6 Sept 1994	13	20	9	9	6	2
28 Sept 1994	-1	16	16	12	9	28
27 Oct 1994	2	12	14	35	-1	11

#### 4.4.3.3 *Plant populations throughout the season and final establishment*

Plant populations during and after emergence up to final establishment are shown in Figure 4.15 and Figure 4.16. On the Dunnington Heath series sandy loam, the losses from the ESept 94, LSept 94 and Oct 94 sowings in the period after maximum population were small except in the Oct 94 Mixed[straw] where 15 plants m<sup>-2</sup> were lost during late December and early January. The extent and timing of these losses were similar to those recorded in the Nov 94 Mixed[straw] sowing. On the Mar 95 and Apr 95 sowings, losses were observed between mid-May and mid-June and early June to mid-July respectively.

On the Fladbury series clay, few losses were recorded in the period post maximum population in the ESept 94 sowing. In the LSept 94 sowing all seedbeds lost plants between early and mid November. In the Oct 94 sowing there was no distinct phase of losses but a gradual reduction in population from mid-December to mid-March.

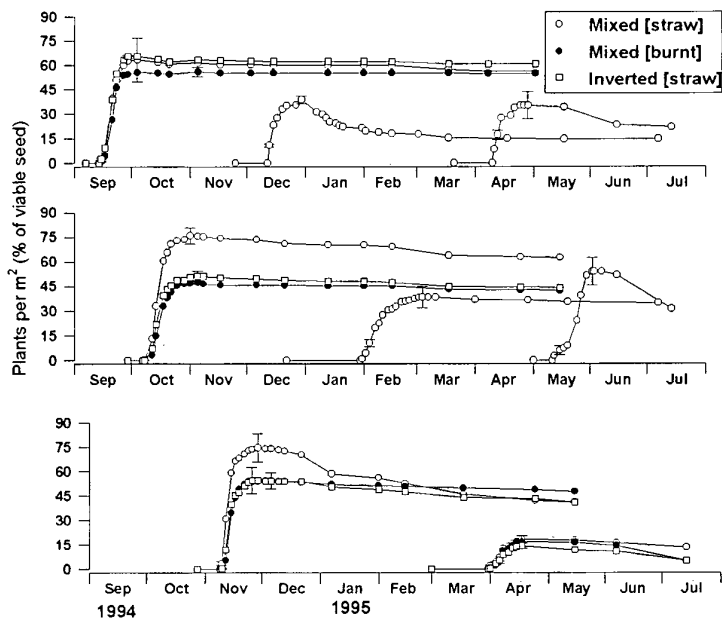


Figure 4.15: Plant counts from eight sowing dates on the Dunnington Heath series sandy loam (Field 9, The University of Nottingham Farm).  
Double standard errors are shown at maximum population.

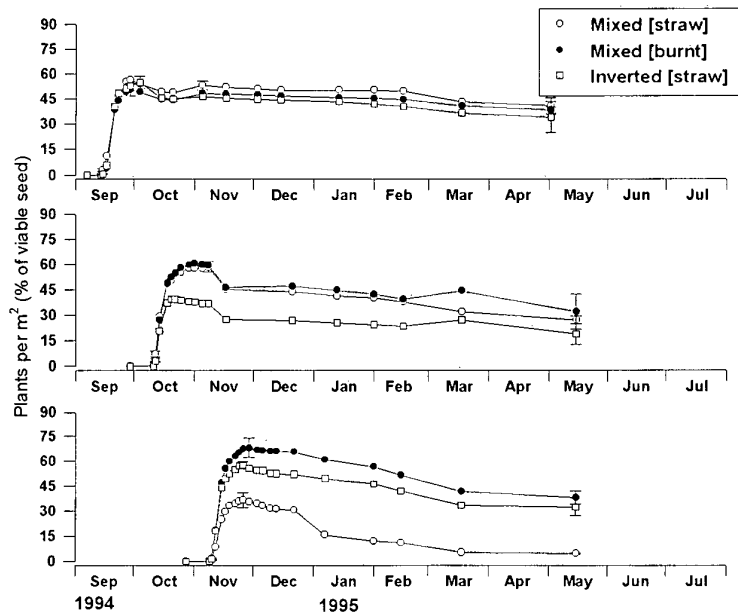


Figure 4.16: Plant counts from three sowing dates on the Fladbury series non-calcareous clay (Field 8, The University of Nottingham Farm).  
Double Standard errors are shown at maximum population and on the final count.

Table 4.15 shows the final established populations expressed as a percentage of viable seeds sown and Table 4.16 as a percentage of those seeds that successfully emerged. Only the LSept 94 sowing produced different seedbed responses on the Dunnington Heath soil, as did the LSept 94 and Oct 94 sowings on the Fladbury soil.

Table 4.15: Final plant populations expressed as a percentage of viable seeds sown m<sup>-2</sup>.

Sowing date	Dunnington Heath sandy loam			Fladbury clay		
	Mixed [straw]	Mixed [burnt]	Inverted [straw]	Mixed [straw]	Mixed [burnt]	Inverted [straw]
ESept 94	57	55	61	41	38	34
LSept 94	63	42	44	27	32	19
Oct 94	41	48	42	5	38	32
Mean	53	48	49	24	36	28

Table 4.16: The proportion of emerged seedlings which survived through to final establishment.

Sowing date	Dunnington Heath sandy loam			Fladbury clay		
	Mixed [straw]	Mixed [burnt]	Inverted [straw]	Mixed [straw]	Mixed [burnt]	Inverted [straw]
ESept 94	86	97	90	62	60	49
LSept 94	81	89	86	66	88	43
Oct 94	53	86	79	12	55	53
Mean	73	91	85	47	68	48

#### 4.4.3.4 Summary of losses in each phase

To summarise the extent of losses in each phase of establishment in each sowing, the number of seeds lost from 100 viable seeds sown was tabulated for each soil type (Table 4.17 and Table 4.18).

Germination in the field, under normal autumn temperatures where water supply was unrestricted, was above 95% i.e. comparable to germination in the laboratory. On the Dunnington Heath sandy loam where sowings were made during winter and spring, losses increased in the Nov 94, Dec 94 and Feb 95 sowings but were lower in the Mar 95 and May 95 sowings. In the ESept 94, LSept 94 and Oct 94 sowings, between 30 and 40% of seeds sown

failed to emerge. Average post emergence losses from ESept 94, LSept 94 and Oct 94 sowings were 11% on the Dunnington Heath sandy loam and 30% on the Fladbury clay.

Table 4.17: Losses (from 100 viable seeds) during germination, emergence and post emergence on the Dunnington Heath series sandy loam.

Sowing	Seedbed	Germination	Emergence	Post Emergence
ESept 94	Mixed[straw]	3	31	9
	Mixed[burnt]	1	42	2
	Inverted[straw]	2	30	7
	<b>Mean</b>	<b>2</b>	<b>34</b>	<b>6</b>
LSept 94	Mixed[straw]	2	20	15
	Mixed[burnt]	1	52	5
	Inverted[straw]	2	47	7
	<b>Mean</b>	<b>2</b>	<b>40</b>	<b>9</b>
Oct 94	Mixed[straw]	5	18	36
	Mixed[burnt]	3	41	8
	Inverted[straw]	3	44	11
	<b>Mean</b>	<b>4</b>	<b>34</b>	<b>18</b>
Nov 94	Mixed[straw]	16	33	36
Dec 94	Mixed[straw]	16	45	4
Feb 95	Mixed[straw]	31	50	5
	Mixed[burnt]	28	57	10
	Inverted[straw]	30	57	8
	<b>Mean (Feb 95)</b>	<b>30</b>	<b>55</b>	<b>8</b>
Mar 95	Mixed[straw]	7	58	13
May 95	Mixed[straw]	12	30	27

Table 4.18: Losses (from 100 viable seeds) during germination, emergence and post emergence on the Fladbury series clay.

Sowing	Seedbed	Germination	Emergence	Post Emergence
ESept 94	Mixed[straw]	3	31	25
	Mixed[burnt]	1	36	25
	Inverted[straw]	2	29	35
	<b>Mean</b>	<b>2</b>	<b>32</b>	<b>28</b>
LSept 94	Mixed[straw]	2	36	35
	Mixed[burnt]	1	39	28
	Inverted[straw]	2	54	25
	<b>Mean</b>	<b>2</b>	<b>43</b>	<b>29</b>
Oct 94	Mixed[straw]	5	53	37
	Mixed[burnt]	3	28	31
	Inverted[straw]	3	36	29
	<b>Mean</b>	<b>4</b>	<b>39</b>	<b>32</b>

## 4.5 DISCUSSION

### 4.5.1 Stage I: maximum emergence and post emergence losses

The Mixed[straw] seedbed produced higher maximum plant populations than the Inverted[straw] seedbed in 9 out of the 11 sowings. Average maximum populations over the eleven sowings, expressed as a percentage of viable seed sown, were 55% in the Mixed[straw] and 44% in the Inverted[straw] seedbed. However, the range of maximum populations over the 11 sowings varied from 32 to 82% of viable seeds sown in the Mixed[straw] and 28 to 63% in the Inverted[straw].

Conversely, between drilling and maximum plant populations, an average of 45% of seed sown failed in the Mixed[straw] and 56% failed in the Inverted[straw]. These data confirmed the findings from the cultivation trials (McWilliam *et al.* 1995) where a large proportion of seeds failed to produce seedlings. In these latest sowings there was no slug or pigeon damage to

confound the interpretation suggesting that all the observed losses resulted from physical attributes of the seedbeds.

The overall higher maximum populations produced in the Mixed[straw] seedbed also confirm the finding from the cultivation trial in which discing gave the highest autumn plant populations. From these studies it would appear, therefore, that cultivations which mix straw in the surface layers actually improve emergence compared to where ploughing has buried the straw.

In the work reported here the different maximum populations in the seedbeds would not appear to be attributable to aggregate size distribution. In most sowings the proportions of large aggregates >23mm and small aggregates <3.4mm were similar in both seedbeds. However, in the Oct 93 and July 94 sowings the seedbed did have statistically different aggregate distributions. In the Oct 93 sowing the Mixed[straw] seedbed had more large aggregates and less small aggregates than the Inverted[straw] but in this case soil moisture content was close to field capacity and water would not have been limited (Section 3.3), nor are the larger aggregate likely to have impeded emergence (Section 3.5). The July 94 sowing, in which the Mixed[straw] had a higher proportion of fine aggregates may have contributed to better seed soil contact and hence water transfer to seed and seedlings especially as soil moisture was close to the -1.5 MPa limit identified in Section 3.3.

The lowest maximum plant populations (less than 40% of seeds sown) resulted from the LNov 93 and Dec 93 and Jan 94 sowings (excluding the Jan 94 Mixed[straw]). These sowings were all drilled when average soil temperatures (at 2cm depth) were below 3°C, conditions which have been shown to reduce germination of rapeseed (Marshall & Squire, 1996; Stokes, Bullard, Scott & Clare, 1997) which may explain the reduced emergence. The first seedlings to emerge took between three and five weeks and the emergence phase was protracted. Peckrun, Lutman & Bauemer (1997b) have indicated that delays in germination can induce secondary dormancy, which may also account for the high losses. However, the thermal time to 50% emergence was no different from sowings made into warmer seedbeds, which suggest that those seedlings which did emerge were not limited by other factors

Although water was not limiting in the autumn and winter sowings, it is clear that this was the main cause of failure in the June 94 sowing. At drilling, the soil moisture was equivalent to -1.5 MPa (the critical threshold, Section 3.3), these conditions of marginal water supply persisted until the end of July. Very few plants emerged during the first two weeks after drilling but later, when rain fell and elevated soil moisture content in the seed zone to a level where water could be expected to be freely available, no further seeds emerged. There are two possible

explanations for this. First the desiccation experiments (Section 3.6) showed that oilseed rape can be killed if the soil dries around the newly emerged radicle and that only a short period of desiccation was required to kill the seedling. The brief increase in soil moisture two days after drilling resulting from a brief shower may have allowed seeds to imbibe sufficient water to elevate seed moisture contents to 40% which, at the prevailing soil temperatures ( $>15\text{ }^{\circ}\text{C}$ ) would trigger germination within 2 days (Kondra *et al.* 1983). However, the absence of rain over the following week coupled with high evaporative demand (Class A pan evaporation of 48mm) led to a further drop in water availability which is likely to have led to seedling desiccation. Alternatively, if seeds did not imbibe sufficient water to trigger germination then the seeds were subjected to prolonged exposure to low soil matric potentials which has been shown to induce secondary dormancy in oilseed rape (Pekrun *et al.* 1997a).

In the May 94 sowing, seedbed structure had a significant effect on emergence. This was linked to the presence of straw in the Mixed[straw] treatment or its absence from the Inverted[straw] seedbed. In the three days following drilling, rainfall events totalling 24mm elevated soil moisture in both seedbeds and soil water was close to field capacity. However, in the subsequent four week period only 8.9 mm of rain fell, compared with an evaporative demand of 170 mm, resulted in a rapid drop in soil moisture and exposed seedlings to a high desiccation risk. The Mixed[straw] seedbed however, always had a higher moisture content than the Inverted[straw] due to the mulching effect of the straw observed in the cultivation trials which buffered the rate of soil drying.

The average thermal time to 50% of emergence was 163  $^{\circ}\text{C d}$  (base  $0^{\circ}\text{C}$ ), similar to the 130-140  $^{\circ}\text{C d}$  reported by Leterme (1988).

Following maximum seedling number, loss of plants Oct 93, ENov 93 and LNov 93 ranged from 11-47% (from 100 viable seeds sown) and between 32-75% of maximum plant population. The regular plant counts made it possible to identify when plant losses occurred (Figure 4.5). The main periods of loss were clearly linked with frost conditions (mean dry bulb temperatures below  $0^{\circ}\text{C}$ ) from the middle to the end of February 1994 confirming the observation by other studies (Single & Marcellos, 1981; Kacperska-Palacz, 1978; Topinka *et al.* 1991). In both treatments, the number of plants lost decreased with later sowing suggesting that smaller plants were more able to withstand frost damage. However, the greater number of losses in the Oct 93 sowing may be explained by the higher maximum population achieved in this instance.

In the Dec 93, Jan 94 or Feb 94 sowings, emergence was slow due to the low soil temperatures and consequently overlapped with the main periods of plant loss observed in the

autumn sowings. It seems likely that seedlings emerged but then died due to the frost conditions but that newly emerged seedlings masked these losses. An important conclusion from this is that losses up to maximum emergence could have resulted either from seeds failing to germinate, seeds germinating and failing to emerge or seedlings emerging but then dying shortly after. In the latter case these losses may be masked by seedlings emerging subsequently and lead to an underestimate of true emergence.

This potential discrepancy was addressed in the second series of experiments in which seedlings were tagged as they emerged in order to assess true emergence as distinct from maximum populations. This, in combination with direct measurements of germination allowed quantitative assessment of losses in each phase to be more precisely defined and related to the seedbed and weather conditions.

#### **4.5.2 Stage II: losses during germination, emergence and post emergence**

##### *4.5.2.1 Sowing to germination*

In the ESept 94, LSept 94 and Oct 94 sowings, on both the Dunnington Heath series sandy loam and the Fladbury series clay, over 93% of viable seeds germinated. In each case the 2-3 week periods following drilling was characterised by soil temperatures above 5°C which would not be expected to limit germination (Wilson *et al.* 1992; Kondra *et al.* 1983) and soil water potentials above the -1.5 MPa threshold for germination identified in Section 3.3.

In the Mixed[straw] Nov 94 and Dec 94 sowings on the Dunnington Heath sandy loam only 84% of seed germinated and in the Feb 95 sowing this dropped to near 70%. The Nov 94 sowing was drilled when soil temperatures were falling rapidly and in 21 out of 30 days after the Dec 94 sowing, soil temperatures at 2cm were less than the 3°C; conditions that have been shown to reduce germination of rapeseed (Marshall & Squire, 1996; Stokes *et al.* 1997). Also, soil water was in excess of field capacity during much of the pre-emergence period indicating that oxygen depletion could have contributed to germination failure (Bradbeer, 1988). The poor germination in the Feb 94 sowing was also associated with soil temperatures below 3°C in 12 out of 30 days after sowing.

Germination was also slightly depressed in the May 95 Mixed[straw] seedbed when temperatures were not limiting. However, between sowing and 12 May, soil moisture never rose above 9.6% and was often at or below the 8%, equivalent to the -1.5 MPa threshold identified in Section 3.3. No further rain fell until 2 June, and although no soil moisture data were available, the high evaporative demand recorded at the Sutton Bonington meteorological site during this period (Class A pan evaporation of 83mm) would indicate that soil moisture would have fallen



below the -1.5 MPa threshold. This may have resulted in desiccation of germinated seed (which has been shown to be fatal - Section 3.6) but which when excavated appeared intact and quiescent and were recorded as ungerminated.

Overall, soil temperatures are unlikely to restrict germination from normal autumn sowings; average soil temperatures at 2cm depth at the University of Nottingham, Sutton Bonington Campus, for August, September and October between 1985 and 1995 were 17, 14 and 10°C respectively. However, if soil conditions are abnormally cold then lower germination is likely. The water potential threshold for germination of -1.5 MPa identified in the laboratory (Section 3.3) also reduced germination under field conditions. Losses may have also resulted from desiccation after radicle protrusion as shown in the laboratory (Section 3.6).

#### 4.5.2.2 *Germination to emergence phase*

Total emergence determined from marking seedlings, confirmed the observations from the maximum populations measured in the cultivation trials and from Stage I of the sequential sowings, that a high proportion of seedlings fail to emerge. In the ESept 94, LSept 94 and Oct 94 sowings between 22 and 52% of plants were lost during emergence on the Dunnington Heath sandy loam and between 28 and 53% on the Fladbury clay. Average losses over the three sowing dates, in the Mixed[straw], Mixed[burnt] and Inverted[straw] were 23, 45 and 40% on the sandy loam and 40, 34 and 39% on the clay, respectively. However, this varied between seedbed types depending on sowing date.

In some cases, all of the losses could be accounted for by depth of sowing, using the equation derived from the controlled environment experiment (Section 3.7). Overall, depth of drilling ranged from 0 to 8cm deep and was closely related with depth of straw incorporation, such that where straw was mixed in the surface layers, the majority of seed were drilled less than 4cm deep and more uniformly.

Comparisons of total emergence and maximum plant populations also showed that turnover of seedlings does occur and that this can mask the difference between emergence losses and post emergence losses. In general, maximum plant populations underestimated the total number of seedlings to emerge by about 5 percentage points but in the ESept 94 sowing on the Fladbury series clay this discrepancy was 16 percentage points. This indicated that, experimentally, it is important to mark plants in order to define the precise timing and hence cause of losses. This detailed approach was used in studies of sugar beet establishment Durrant (1981) and Durrant,

Dunning, Jaggard, Bugg & Scott (1988) and facilitated much more accurate analysis of cause and effect. This approach is however, very time consuming in oilseed rape studies due to the higher plant populations which could preclude its use in large scale experiments.

#### 4.5.2.3 Post emergence phase

Post emergence losses on the ESept 94 and LSept 94 sowings on the Dunnington Heath sandy loam were less than 15%. Losses were higher in the Mixed[straw] treatment from these two sowings and the difference was even more pronounced in the Oct 94 sowing where the Mixed[straw] lost 36% compared to only 8% in the Mixed[burnt]. The main difference between these seedbeds was that the presence of straw increased the soil moisture above field capacity, although the period of plant loss followed frost conditions during November and December. Waterlogging has been shown to predispose plants to frost damage and *vice versa* (Smith & Olien, 1981). The link between excess soil water, frost conditions and plant kill also applied to the ESept 94, LSept 94 and Oct 94 sowings on the Fladbury series clay. Overall, losses were higher on the Fladbury series clay on which all the seedbeds had soil moistures above field capacity for most of the period between November and March and often had standing water. On the Dunnington Heath sandy loam, losses were higher on the wetter Mixed[straw] treatment than on comparatively drier Mixed[burnt] seedbed.

Losses from the ESept 94 sowing followed a period of high rainfall which elevated the soil moisture to 53% (Figure 4.17 point a), well above field capacity (45%); this coincided with maximal emergence. Losses of about 15 plants m<sup>-2</sup> were observed in the three weeks which followed as damage caused by the waterlogging took affect. Further losses were prevented by a period of dry weather, with an associated drop in soil moisture. When the soil moisture again rose above field capacity during November (Figure 4.17 point b), plant losses were negligible, probably because the plant had grown rapidly during the drier period and were more tolerant. In the LSept 94 and Oct 94 sowings, the soil moisture was below field capacity during the emergence phase and although some fatalities were observed prior to the rise in soil water, the main losses (15 plants m<sup>-2</sup>) were linked with a rise in moisture content to 60% (Figure 4.17 point b). A slight reduction in soil moisture to 50% during November led to a cessation in plant fatalities; as soil moisture again rose to 60% during December and was sustained through January (Figure 4.17 point c) and February, further plant losses were observed; by mid-March these accounted for an additional loss of 13 plants m<sup>-2</sup>.

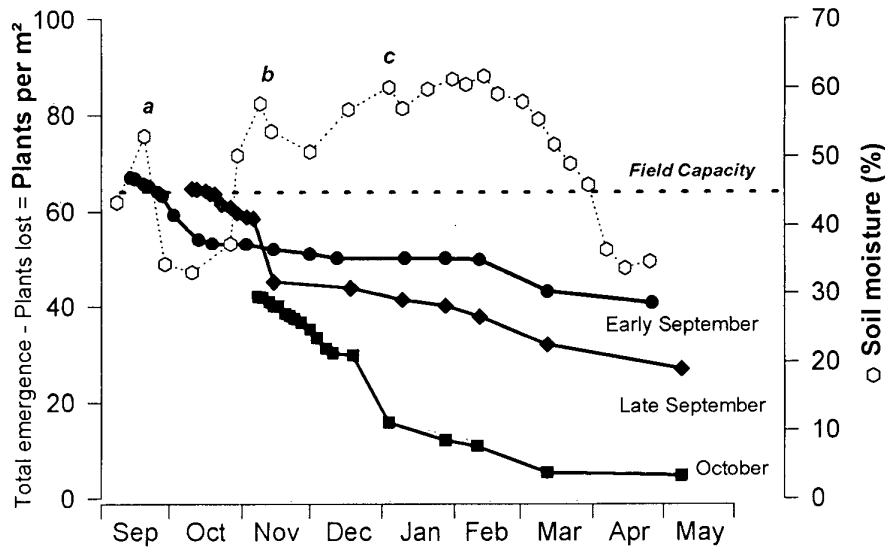


Figure 4.17: The effect of soil moisture on post emergence losses in the Mixed[straw] treatment from ESept 94, LSept 94 and Oct 94 sowings on the Fladbury series clay [Field 8, The University of Nottingham Farm].

Post emergence losses of 27% were recorded in the May95 sowing on the Dunnington Heath sandy loam; in this case, temperatures were high and soil moistures were low. The soil moisture at drilling was sufficient for emergence but the subsequent high evaporative demand and low rainfall receipts reduced the soil moisture to below the permanent wilting point, resulting in seedling failure during June. This example illustrates the potential for plant losses where oilseed rape crops have been drilled in August, emerged following rain and then experienced a dry autumn.

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## 5. GENERAL DISCUSSION AND CONCLUSIONS

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### 5.1 ESTABLISHMENT - CRITICAL SEEDBED FACTORS

The current limitation to autumn establishment of oilseed rape is the ability to prepare a seedbed which confers a physical environment which does not impede growth and minimises the adverse effects of the weather and biotic factors.

Previous studies on oilseed rape establishment have focused on different cultivation methods in order to identify the implement that gave the best establishment (Darby & Yeomans, 1994). However, from the cultivation experiments reported by McWilliam *et al.* (1995) it was shown that no single 'engineering solution' could be applied since the effect of cultivation implements depends on the state of the natural seedbed, the soil type as well as the soil moisture status. Furthermore, the weather conditions after drilling are known to play a major role in determining establishment (Darby & Yeomans, 1994). This identified the need for a greater understanding of the establishment process in order to identify how the physical characteristics of the seedbed interacted with the weather to determine the success or failure of seeds and seedlings. This problem was approached by splitting up establishment into three distinct phases of germination, emergence and post emergence growth in order to show when and how losses occurred. The work reported here has quantified through laboratory and field studies some of the critical physical factors that operate in one or more of the phases.

#### 5.1.1 Germination

Temperature, water and oxygen are the main factors limiting germination. The thermal requirement for germination of *Brassica napus* under laboratory conditions is about 25 °C d (Kondra *et al.* 1983) and in double low UK cultivars at base temperature of 3°C. In the current study a field sowing in December, when average soil temperatures were below 3°C, reduced overall germination by 16%. In a February sowing, where low temperatures were combined with high soil moistures (in excess of field capacity) overall germination fell by 30%. However, 'normal' soil temperatures during August, September and October did not restrict germination of oilseed rape and over 93% of seeds germinated. The main factor that restricted germination was water supply.

In a laboratory study (Section 3.3), germination (radicle protrusion) was associated with seeds which attained a moisture content of approximately 40 % (W/W), similar to moisture

threshold for other crop species (Hunter & Erikson, 1952). Prior to radicle protrusion seeds were able to tolerate desiccation after initial imbibition without reducing subsequent viability (Section 4.6).

The current study (Section 3.3) showed that soil water potentials below zero reduced the rate of germination and total germination. A water potential ( $\psi$ ) -1.5 MPa was identified as the critical threshold for germination. This threshold helped explain observed delays in emergence at low soil moisture in cultivation experiments (McWilliam *et al.* 1995). Pekrun *et al.* (1997a) showed that if oilseed rape seeds were exposed to low water potentials for extended period then this induced secondary dormancy. The importance of this was confirmed under field conditions where germination was reduced following drilling into a seedbed which remained at -1.5 MPa for three weeks after drilling.

The soil water matric potential, at a given moisture content, is known to be dictated by the soil textural qualities (% clay, silt and sand). Combining the water potential threshold for rapeseed with a knowledge of the water release characteristics for specific soils allowed greater interpretation of instances of delayed emergence (germination) (Section 3.2). In a practical context, this can provide a predictive tool for indicating when soils will be too dry for germination or where cultivations to create a seedbed may reduce soil moisture below the threshold and hence be inadvisable.

### 5.1.2 Emergence

The emergence phase represents the extension of the hypocotyl above ground level. In the current study, the majority of plants were lost in this phase (Section 4.4). In some cases up to 60% of seed sown were lost and the smallest loss was 18%.

The growth and development of the hypocotyl requires energy which is supplied through respiration of the stored oils in the seed. The amount of oil reserves determines the total potential energy available. The physical properties of the seedbed influence the depletion of these reserves by physically impeding the hypocotyl extension, which in turn, governs the speed of emergence and hence the risk of exposure to desiccation, disease and pest damage.

The total energy required to get the hypocotyl to the surface is a combination of the sowing depth and the resistance to penetration. Laboratory studies (Section 3.7) showed that sowing depths greater than 5cm significantly ( $P < 0.05$ ) reduce emergence with optimum emergence at depths less than 3cm deep. However, in field conditions (McWilliam *et al.* 1995) drilling into the surface 2 cm of the seedbed increases the risk that seedlings will experience desiccation. Taking both depth and desiccation risk into account it is concluded that the ideal drilling depth is 2-3 cm.

Achieving consistent drilling depths was shown to be a key limitation to emergence (Section 4.4). Consolidation of the seedbed to improve control over drill penetration is therefore advocated but this must be balanced with the adverse effects of increased bulk densities in the seedbed surface. Experiments conducted under laboratory conditions (Section 3.8) showed that for an alluvial clay (47% clay, 32% silt and 19% sand) at a moisture content of  $\approx 40\%$  (field capacity), increasing the bulk density of the 2cm of soil covering the seed from 1.1 to 1.2 g cm<sup>-3</sup> reduced emergence for seeds >2mm diameter from 80% to 50% and in seeds <2mm this was even more pronounced, 70% to 25%. In a sandy loam (14% clay, 25% silt and 61% sand), bulk density was less critical, significant reductions were only associated with bulk densities in excess of 1.5 g cm<sup>-3</sup>. The effect of increased bulk densities was partially (but in these experiments not significantly) offset by sowing larger seed, which may provide a mechanism for improving emergence under adverse conditions.

High bulk densities near the soil surface can develop as a result of mechanical compaction or smearing, for example, by a set of rolls operating at soil moisture levels close to the lower plastic limit applicable to the specific soil. Loss of aggregate structure can also result from the impact of rain droplets. The extent to which slumping of aggregates occurs is dependent on the stability of the aggregates. Soil with high silt contents and low organic matter are most vulnerable; within clay soils those with low calcium carbonate content are most at risk. Within any soil class, artificially formed aggregates, which are pre-wetted are most predisposed to structural collapse (Davies *et al.* 1993). From a practical perspective the aim should be to capitalise on existing aggregates by avoiding compacting the surface layers of the tilth during harvest and avoiding deep cultivations which bury the fine tilth.

A fine tilth has been shown to improve seed soil contact and reduce surface evaporation (Braunack & Dexter, 1989b). A fine seedbed may therefore help to reduce the desiccation risk to emerging seedlings which are vulnerable to dehydration (Section 3.6). However, extensive cultivations to impose a fine structure predispose the soil to erosion, as discussed above. Furthermore, contrary to the perception of growers, the work reported in this study suggests that large aggregates in the seedbed do not impede emergence as long as soil moisture is not limiting.

### 5.1.3 Post emergence

Post emergence growth and development is determined by solar radiation, temperature, nutrient supply, water supply, pests, diseases and weed competition. The success of emerged seedlings in the autumn is closely linked with the rate of growth since large fast growing plants are able to “grow away” from damage by pests and diseases and competing weeds.

The main factors determining plant survival over winter in the current study were frost and soil moistures in excess of field capacity. Plants subjected to anaerobiosis associated with waterlogging are more susceptible to frost damage and *vice versa* (Smith & Olien, 1981) and this additive effect was observed in the current study (Section 4.3); in the most extreme case, 37 plants per m<sup>2</sup> were lost.

Obviously both rainfall and temperature are seasonally dependent. However, waterlogging is more likely on poorly drained non-calcareous clays (Davies *et al.* 1993). In addition, the current study has shown that the presence of straw on the surface, or mixed in the upper layers of the soil profile, increases the soil moisture relative to where no straw is present or where it had been buried by ploughing. Oilseed rape is relatively tolerant to frost damage and develops tolerance by pre-exposure to low temperatures but this is dependent on an adequate assimilate supply (Kacperska-Palacz, 1978; Kacperska-Palacz & Weislińska, 1972). This would explain why earlier sowings suffered fewer losses in the current study.

In summary, the experiments reported here have provided part of the understanding behind previous empirical measurements of establishment. In the absence of pests, most losses (between 30-40% of seed sown) occurred during the emergence phase and could be attributed to depth of sowing, water availability and soil impedance. Post emergence losses accounted for between 2 and 39% of seeds sown and were most acute where saturated soils were combined with frost conditions.

There is scope to reduce the risk of seed and seedling failure through more detailed attention to seedbed preparation. Creating a very fine seedbed after burying any cereal residues should not be the primary objective but instead, seedbed preparation should seek to produce a firm stable structure which will provide sufficient moisture to initiate rapid germination and emergence while having good underlying drainage properties.

The first step must be to examine for the presence of natural tilth. If the tilth is present, deeper cultivations which bury these stable aggregates and increase moisture loss should be avoided in favour of cultivations which mix straw in the upper layer. The effects of straw were more closely related to the effects that their disposal has on the physical characteristics of the seedbed rather than the secondary, more direct effects arising from decomposition. Consequently burying straw is unnecessary provided it has been spread evenly during combining. Straw mixed in the surface layers was actually shown to have positive effects; by reducing drill penetration and thereby controlling drilling depth, reducing evaporative losses, reducing slumping and may also provide an alternative food source for slugs and so reduce grazing on

plants. Overall, discing provides a good compromise between mixing straw in the seedbed, retaining natural tilth while minimising moisture loss.

Most losses occurred during the emergence phase. Here, improving seed quality could provide a mechanism to reduce the risk of emergence losses, especially where seedbeds are compacted or where seeds have been drilled below the optimal depth of 2-3cm. Larger seed with greater reserves are better able to overcome such adverse conditions.

There seems every justification to proceed with the exploration of the hypothesis that the physical environment of the seed bed can be improved by operating machinery on the basis of the condition of the natural structure of the seedbed (exploit the natural tilth), with the least expense required to give the satisfactory outcome. The findings in this report need to be tested in contrasting soil structures by contrasting best and worst of conventional practice. However, before this can be attempted, the indication that the seed itself can have a significant influence on establishment must be evaluated to ensure no approach to improving establishment is missed.





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