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FACTORS AFFECTING CEREAL ESTABLISHMENT AND ITS PREDICTION

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by

J J BLAKE[1], J H SPINK[1] AND C DYER[2]

[1]ADAS Rosemaund, Preston Wynne, Hereford HR1 3PG.
[2]ADAS Gleadthorpe, Meden Vale, Mansfield, Notts. NG20 9PF

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Contents

SUMMARY

Previous HGCA-funded research has shown that significant reductions in spring plant population are possible compared to the traditional figure of 275 plants per m^2 (Spink et al. 2000). As growers move towards lower target plant populations the margin for error in terms of estimating the percentage of sown seeds that will produce plants is reduced. Improving prediction of seedling emergence and over-winter survival, through a better understanding of the major factors affecting germination and seedling growth, is therefore key to optimising seed rates and plant populations in cereals.

A large number of factors affect establishment. This review attempts to quantify the effects of a range of factors with a view to improving prediction of percentage establishment likely in any given situation. Two approaches have been used: a review of existing scientific literature; collation and analysis of experimental results where establishment was measured.

The collated database consists of some 1250 individual records from a broad range of experiments from 27 different sites over the last 25 years. The overall average autumn establishment was 67%; this however masked significant variation with actual establishment varying from 2 – 100%. The average establishment is surprising and should be an immediate cause of concern, as the generally accepted benchmark figure for wheat is 85%. Additionally, experimental work is usually sited in the better areas of fields and receives greater care and effort than do many commercial crops; as such establishment achieved would be higher than in commercial practice.

The literature review indicated that the physiological processes involved in germination are well understood. This understanding, whilst of little immediate practical use, forms the basis for understanding how factors affecting establishment in the field affect the physiological process. A number of seed factors also have consistent, although generally not large, effects on establishment. For example, there are many reports that large seed results in better establishment, but reducing seed size from 61 to 26 g thousand grain weight only reduced establishment by 6%. There are also a number of factors influenced by parent crop management and seed storage, which could improve seed quality and may be worthy of further investigation and ultimately incorporation into seed production protocols. These factors could not be further investigated as few records of seed sown are maintained as a routine in field experiments.

The literature review indicated the importance of a range of soil characters that affect the ability of the seed to germinate and subsequently emerge. Those affecting germination could be summarised as those which affect seed-to-soil contact or soil water status and therefore the rate and duration of seed imbibition. Factors affecting emergence were largely those that influenced impedance, for example clod size distribution or sowing depth. These factors could not be tested directly in the data review; again few quantitative records of sowing depth, seedbed quality or soil moisture are taken routinely in field experiments.

Records of cultivations are fairly routinely made, so these were investigated. There were no large or consistent differences between primary methods of cultivation on establishment. There were however significant differences between secondary cultivation methods and with rolling. Rolling is generally carried out to improve seed-to-soil contact and, assuming it was only carried out in appropriate situations, would be expected to improve establishment, which it did by about 10%. Three main forms of secondary cultivation were used: power harrowing, discing or tined cultivations. Tined cultivation was the most successful with 80% establishment compared to 62-66% for the other two methods. No immediately obvious explanation could be found, and it may be worthy of further investigation. Meteorological records were collected for each of the sites and rainfall pre- and post sowing and soil temperature investigated to look for consistent effects. Perhaps surprisingly there were no effects of rainfall, but there were consistent effects of soil temperature. Contrary to many laboratory based experiments, which have been reported indicating optimum temperatures of 20-25^{o}C, optimum soil temperatures (at a depth of 10cm) in the data review were 8-12^{o}C for earlier drillings and 12-16^{o}C for later drillings. The different optimum temperatures according to sowing date were thought to be due to interactions with soil moisture. These soil factors vary in the degree to which the grower can manipulate them; they all, however, are open to measurement using precision farming techniques. If such methods could be developed this would enable improved precision in seed rate used within fields resulting in more uniform crop stands, and less within-field variation to subsequently manage.

Other factors considered in the data review, which did not figure significantly in the literature, were soil type, previous cropping and variety. A large number of soil types were included in the data set but all soils were grouped into sands, loams and clays. There was little difference between the clays and loams with establishment averaging 60-65%; sands were significantly better however with establishment averaging nearly 90%. Although a grower has little control over their soil type, an effect as large as this is worthy of inclusion in any future establishment prediction system. Previous cropping had a significant effect on establishment; wheat crops following oats had the best establishment (79%) and the worst was following beans at 54%. The degree to which these effects were real, or due to confounding of, for example, crop type and soil type or sowing date was hard to establish. However, there were cases where previous crop may have affected pest or disease incidence and therefore establishment of the following crop.

Perhaps the most surprising result was the significant effect of variety. Seven varieties for which there were a sufficiently large number of records were assessed. Establishment varied from 73% for Claire down to 61% for Spark. This effect may in part be due to seed size but there may be other inherent genetic effects that could be exploited by breeders.

Over-winter survival is important as spring plant population influences yield potential. The literature review indicated that little work has been carried out on the subject. Ongoing seed rate work has, however, indicated that in some circumstances it can be a considerable effect. Additionally, in the data review, whilst there was insufficient data where both autumn and spring population was recorded to do a formal analysis, spring populations in some regions were about 15% lower than autumn populations.

A number of significant biotic factors were identified. Again these are rarely quantitatively recorded in field experiments and could not be further investigated in the data review. The major pests identified included slugs, frit fly, leather jackets, wheat bulb fly and wireworm. Whilst a reasonable amount is known about each in terms of life-cycle, and factors which affect pest population, little has been done to quantify damage they cause and how this interacts with the crop to cause yield loss. Research to investigate these interactions could contribute significantly to prediction of establishment but also targeting of pest control treatments. One main group of pests largely absent from the literature was birds; this probably reflects the difficulty of carrying out research into the damage they do, rather than their importance. Significant improvements in establishment prediction could be made if suitable experiments to understand more fully their importance and suitable mitigation strategies can be designed.

The two main disease problems identified in the literature were fusarium seedling blight and septoria seedling blight. Whilst both can significantly reduce establishment, both are easily controlled by either use of clean seed or seed treatment fungicides.

Seed or parent crop management was identified as one area that has received less attention. The impact of nitrogen strategies on grain nitrogen, grain size and homogeneity may all impact on likely field establishment, especially where crops are sown in less than ideal conditions. Optimising management of seed crops could improve growers' confidence in expected establishment.

Several models have attempted to predict establishment. Bouaziz and Bruckler (1989b) under dry conditions in S. America focused on factors of most influence in that environment, namely water potential and temperature. Techniques to characterise seedbeds by video image analysis (Stafford & Ambler, 1990) and sensing of soil water content from mobile machinery (Whalley & Stafford, 1992) provide tools and real time information on seedbed quality. However interpretation of this information alone is insufficient to provide the basis of a model of establishment. This review and data analysis indicates that, although soil moisture and temperature have significant effects, many other factors have to taken into consideration if a model of establishment is to be safe and accurate in a given field situation. A predictive model for use under UK conditions could make use of the available algorithms. A model that fully accounts for establishment under UK conditions would also need to consider water availability, waterlogging and oxygen availability. Such a model would be improved by accounting for both soil and seed characteristics, over-winter survival, and the potential risk of pest damage.

This review of the scientific literature and the collation and analysis of results from a large number of experiments has identified many factors which are important in seedling establishment. However, it has also identified a serious deficiency in the monitoring and appropriate measurement of seedbed characteristics, which are essential in predicting seedling establishment. This lack of monitoring of soil and seedbed conditions even extends to those experiments claiming to compare different soil management and seedbed cultivation systems. Research focused on improving the growers ability to predict establishment more accurately by developing simple measurements and observational techniques, will increase growers confidence in reducing seed and cultivation costs. This information could provide both direct information to the grower as well as be used to strengthen a predictive model of establishment.

1 INTRODUCTION

Previous HGCA-funded research has shown that significant reductions in plant population are possible (Spink et al. 2000), particularly with early sowings and to a lesser extent with later sowings. The results indicated that for an end of September sowing, traditional target plant populations of 275 m^{-2} can be reduced to as low as 60 m^{-2} with no effect on yield, resulting in savings of around £35/ha. These lower density crops have also been shown to have lower lodging risk. However, uncertainty about the proportion of seed sown that will establish and over-winter, means that seed rates in many cases are much higher than is needed.

Traditionally an average establishment of 85% of seeds sown has been assumed from fungicide treated seed, which has been used routinely on a precautionary basis. Growers have then refined this expected establishment figure, usually downwards, on the basis of prevailing climatic and soil conditions and perceived risk of pest attack. These refinements have rarely been based on a quantitative assessment of the impact of the various factors; indeed many growers do not keep records of the number of seeds sown or the number of plants established. Because of this uncertainty, alterations to the expected establishment figure generally err on the side of caution, resulting in more seeds being planted and more plants being established than necessary. As growers move towards lower target plant populations and the potential loss is greater from establishing less than the target number than from establishing more, the degree of insurance built into the estimate of establishment increases. Improving the prediction of seedling emergence, through a better understanding of the major factors affecting germination and seedling growth, is therefore key to optimising seed rates and plant populations in cereals.

A plant can be considered as established once the seedling becomes autotrophic and is no longer reliant on its endosperm. However, previous research on plant populations (Spink et al. 2000) specified the minimum spring plant population needed to maximise crop gross margin, as such over-winter survival also needs to be considered.

Previous approaches to understanding the physiology of establishment (Bouaziz and Bruckler, 1989a,b) have separated the process down into 3 stages: imbibition and germination, root and seedling growth, and seedling emergence. However, most external factors affecting establishment impact on all stages. As the purpose of this report is to review major factors affecting establishment, all three stages will be considered together and the factors grouped into inherent seed factors and external abiotic and biotic factors. Before considering the how various factors affect establishment it is useful to understand the physiological processes occurring within the seed.

1.1 Imbibition

In cereals germination follows a hypogeal pattern, with the remnants of the seed remaining below the ground whilst the first leaf emerges through the coleoptile. The first stage in the germination process is imbibition. During this phase, water penetrates the seed coat and softens the hard, dry tissues inside. Hydration of the seed activates the biochemistry of the embryo and the plant hormone gibberellic acid (GA_3) inside the embryo becomes dissolved in the incoming water and is transported thorough the rest of the seed tissues (figure 1.1).

In wheat, a critical seed moisture content must be achieved before the rest of the germination process can occur (Bruckler, 1983). In general, seed water content must reach at least 35-45% of grain dry weight; however wheat germination is possible at seed water contents of as low as 27% (Bouaziz and Bruckler 1989a). This is probably the moisture at which a sufficient level of biochemical activity can occur. The rate of water uptake is controlled primarily by the hydraulic conductivities of the soil and seed epidermis, and by the extent of the seed-soil contact, as described later. Under very wet or nearly saturated conditions the oxygen diffusion rate becomes a limiting factor, so despite the imbibition process occurring as normal, the rate of the latter stages of germination is checked. Seed germination can be said to have occurred when growth of the radicle bursts through the seed coat and protrudes as a young root (Koning 1994).

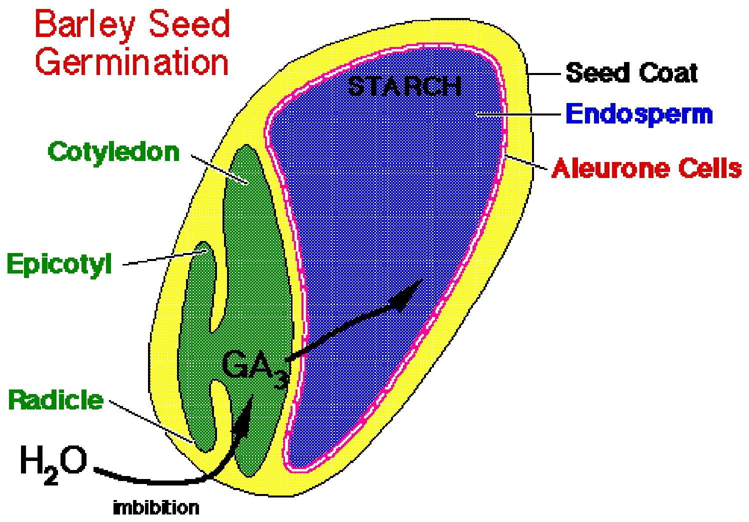

Figure 1.1. A diagram illustrating imbibition in barley seed (*Hordeum Jubatum*), (courtesy of Ross Koning, 1994). This figure shows the process in barley seed for illustrative purposes - the processes involved in wheat germination are identical.

1.2 Biochemical processes

At the aleurone layer, surrounding the endosperm, the gibberellic acid triggers the aleurone cells to produce and secrete the enzyme amylase. Amylase acts as a catalyst for the hydrolysis of starch in the endosperm into its component sugars (Koning 1994) (figure 1.2).

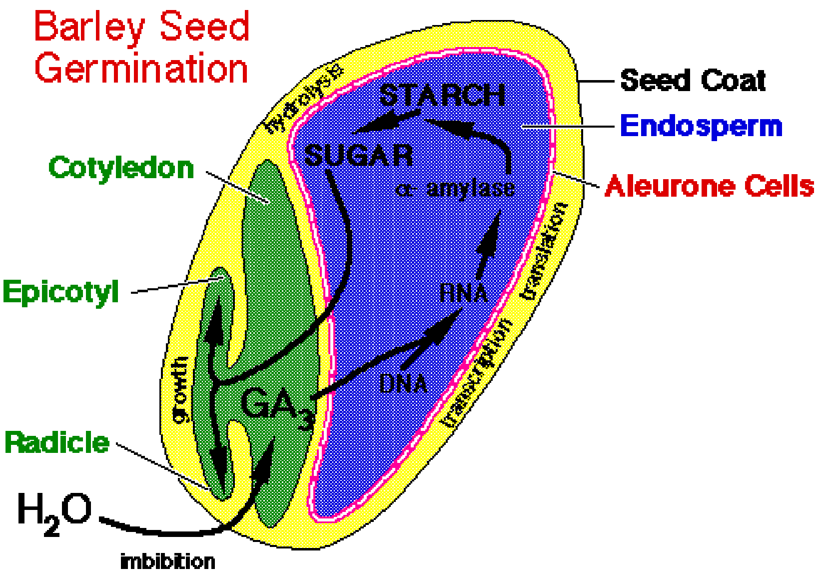

Figure 1.2: Pre – germination biochemical processes in barley seed. (courtesy of Ross Koning, 1994).

1.3 Seedling growth and emergence

1.3.1 Development of the radicle (seminal roots)

The embryo possesses five roots, a primary radicle and two pairs of lateral rootlets. Following imbibition the coleorhiza (root sheath) expands, splitting of the seed coat, and at the same time the primary radicle and the first pair of seminal rootlets break through the coleorhiza, this being followed shortly after by a second pair (Lockhart and Wiseman, 1993).

1.3.2 Development of the coleoptile

As the root system is being formed at the base of the stem, the plumule starts to grow upwards, and the coleoptile appears above the ground as a single pale tube-like structure. The coleoptile protects the first leaf as it pushes its way through the soil to the surface during emergence. The first leaf emerges through a slit in the top of the coleoptile. This is subsequently followed by others at phylochron intervals (Lockhart & Wiseman, 1993).

In wheat and barley, the coleoptile develops from the second or the third node on the plant. Under shallow planting conditions the nodes beneath the crown remain short and the coleoptile originates from the level of seed. Where seeds are planted deeper in the soil, the internode between the coleoptilar node and the next lower node, often called the subcrown internode, has the ability to elongate up to 8cm to position the crown within one inch of the soil surface. At planting depths greater than three inches the next higher internode may also elongate (Percival, 1921)

2 LITERATURE REVIEW

2.1 Seed-related factors affecting establishment

A number of seed related factors may affect germination and establishment, including dormancy, seed size, parent crop nutrition and autotoxicity. The germination capacity of cereal seeds is the percentage (by number) of seeds which show the radicle (young root) during the period of the germination test. Almost 100% is possible, 95-98% is common, below 95% is unacceptable. Ideal conditions of moisture, aeration and temperature (20^0C) are provided (Wibberley 1989). To pass UK certified seed criteria seed lots must have been tested at over 95% germination. Field conditions are however rarely close to the standard conditions set in the laboratory, and the increased use of farm-saved seed has meant that not all seed undergoes germination testing.

2.1.1 Dormancy

A degree of dormancy can be of value in cereals, as it may help to prevent sprouting following periods of high rainfall pre-harvest (Belderok, 1961). Although long-term dormancy is not considered a problem in cereals, barley, and to a lesser extent wheat and oats, can exhibit a temporary dormancy. In contrast, other cereals such as triticale, rye, and durum wheat have been noted for their susceptibility to pre-harvest sprouting (Derera, 1980), a condition that is known to be inversely related to dormancy (Black et al., 1987).

In barley the causes of dormancy are not clear. Its development during grain filling has been linked to cool temperatures, as cool temperatures retard after ripening and loss of dormancy (Pickett, 1988). Dormancy has also been linked to variety, the now outclassed spring cultivars Triumph and Doublet were notorious for developing intense dormancy (Briggs and Woods, 1993). Tests attempting to break dormancy in these varieties, have found that antibiotics can break dormancy by killing surface microbes. These microbes have been shown to consume considerable amounts of oxygen, suggesting the embryos of dormant seeds need a more ready supply of oxygen to germinate than those of mature grains (Briggs, 1992).

Dormancy has generally been overcome by storing grain for extended periods, creating the necessity for maltsters to carry over stocks from one season to the next to allow malting to proceed until the new seasons crop has lost its dormancy (Briggs, 1992).

Warm drying and warm storage (30-40^0C) is also known to accelerate the decline in dormancy in dormant barley cultivars (Pollock, 1962). The expression of dormancy has also been shown to depend on the conditions of growth, such a temperature and water availability (Briggs 1978). Thus barley germination tests may not fully represent the potential field establishment.

Although we might generally view field conditions as being less favourable than the standard germination conditions, in oilseed rape large daily temperature variations such as those achieved near the soil surface in field conditions have been shown to break dormancy (Lutman et al., 1998). It may be that in barley field conditions may be more favourable than constant temperature germination conditions used in laboratory testing. For growers farm saving barley seed, it is worth noting that initially poor germination test results may improve as planting approaches if seeds are dormant, especially if the seed is being stored under warm conditions. The link between dormancy and cool temperatures during grain fill suggests that barley crops grown at higher latitudes may be more susceptible to the onset of dormancy; this was found with Triumph, with dormancy being associated with crops grown in the north of England and Scotland (Briggs and Woods, 1993). Dormancy has also been noted as problematic in the 3 to 4 weeks after harvest in some 6-row barleys, where a 7 day pre-chill treatment prior to germination testing was insufficient to break dormancy. In spring-sown cereals dormancy has not been considered problematic due to the time delay between harvest and sowing generally being sufficient with modern varieties to allow maturation to occur (D. Spencer pers. comm.). That oxygen requirements are higher in immature seed for germination to occur could have management implications in some locations, however generally under UK conditions the wet, oxygen limiting seedbeds, are more likely to be found later in the autumn planting season after seed lots have had sufficient time to mature.

2.1.2 Seed size

Numerous studies have showed that early growth and vigour of many species are affected by seed size and weight (Kittock and Law, 1968; Ries and Everson, 1973; Naylor, 1993). Naylor showed that increasing the seed size had a small but positive effect on the final % germination in wheat (figure 2.1).

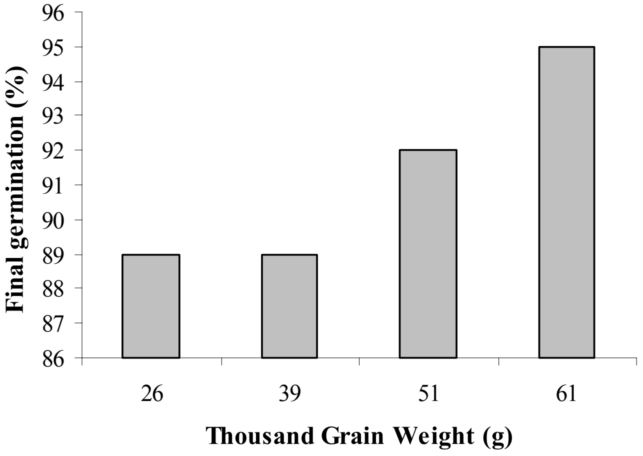

Figure 2.1 The effects of grain weight on percentage germination at 18^0C (Naylor, 1993)

This experiment was carried out under standard laboratory conditions in petri dishes in a germination room maintained at 18^0C. Further work by Naylor looked the germination of large and small wheat seeds at a range of temperatures. This showed that whereas both seed lots achieved very high germination levels around the optimal temperatures, larger seeds appeared to be less affected by the extremes of temperature, with smaller seeds tending to have much poorer germination at temperatures below 10^0C. This suggests that the additional cost implications of sowing larger wheat seeds may be, in part, balanced by better emergence under field conditions.

2.1.3 Parent crop management

2.1.3.1 Nutrition

The influence of fungicides and nitrogen applications to parent crops has been shown to affect subsequent seed size and storage protein concentrations in the harvested seed. Fungicide use has been consistently linked with increased grain size and weight (Taylor and Blacket, 1982; Jordan, 1992), presumably by helping to maintain green area late in to the season. Separate studies have found conflicting effects, with nitrogen applications, being shown to increase, reduce and have no effect on grain size. Taylor and Blacket (1982) in a survey of 11 trials on spring barley from 1975 to 1979 showed that in one season the proportion of large grain was not influenced by application of nitrogen to the parent plants but in two other seasons the proportion of large grains declined above 60 kg N ha^{-1}. Naylor (1993) also showed that although nitrogen applications increased yield by increasing grain number m^{-2} it also increased the proportion of smaller grains. However ongoing HGCA-funded work across several sites and seasons suggests that increased N applications increase thousand-grain weight in spring barley (Wade, pers. comm.). Additional late fungicide applications also, in many cases, result in increased thousand grain weights. It is likely the impact of nitrogen on grain size is affected by the timing of nitrogen availability to the plant, as this will impact on resource allocation to the various components of yield. It might be expected that where nitrogen is available to the plant early in the season, this will result in a proliferation of shoots and large quantities of partially filled grains at the end of the season. If nitrogen is applied later, after tillering and grain number per ear has been determined, additional leaf greenness may result in better grain fill.

Increased parental N applications have been shown to increase grain nitrogen content (Naylor, 1993), as well as affect the amino acid composition of the grain protein usually increasing the deposition of storage proteins (Larsen et al., 1966). In Naylor’s work (1993) final germination was reduced, and germination delayed only when nitrogen applications to the parent crop were limited to 50 kg N ha^{-1}. This suggests that only at such low nitrogen applications are the enzymes (or precursors) required for germination present in limiting quantities.

2.1.3.2 Vigour

Whilst the germination test assesses the seeds capacity to germinate under ideal laboratory conditions, Vigour tests have been developed (Hayward, 1978) that aim to screen seed samples to ensure they have adequate and uniform capacity to grow sturdily in the more testing conditions in the field. As discussed earlier Naylor (1993), showed that parental crop nutrition may affect the ability of a seed crop to germinate and establish effectively. Vigour has also been linked to plant breeding and genetics (Wibberley, 1989). One possible reason for this is that cultivars may differ in their partitioning of resources to the roots and shoots and that under low soil water potential conditions fast-rooting lines emerged better (Gul and Allan, 1976).

As seeds age they progressively lose their vigour and then viability (Briggs and Woods, 1993). Seed storage conditions can affect the rate of physiological ageing, higher temperatures increasing rate of loss of vigour and viability. Seed storage in an atmosphere of carbon dioxide has been shown to have a negative effect on subsequent germination levels (Briggs 1992). On occasions, both merchants and growers carry over seed from one year to the next due to poor autumn planting conditions. The germinability of this seed may depend on the conditions of storage. All seed will respire in storage, generating carbon dioxide. It is possible that year long storage of seed in sealed 500kg bags may create a less favourable environment for long term storage, as respiring seeds is likely to generate high levels of carbon dioxide reducing the germination potential of the seed lot.

2.1.4 Allelopathy and autoxicity

Allelopathy refers to the detrimental and beneficial biochemical interactions between plants (Molisch, 1937). Autotoxicity is an intraspecific type of allelopathy that occurs when a plant species releases chemical substances that inhibit or delay germination and growth of the same plant species (Putman, 1985). The release of phytotoxic substances (allelochemicals) by a plant is a method by which it can prevent other seeds and seedlings growing, and competing for resources in its proximity. Wheat seedlings, straw and aqueous extracts, have allelopathic effects on a number of agricultural weeds (Shilling et al 1985, Wu et al 2000), as well as its own seedlings. Wu et al (2000) demonstrated that wheat seedlings were able to synthesize and exude phytotoxic compounds through their root system, into the surrounding medium. The extent to which this may affect establishment will depend on the proximity of seedlings and the potency of the allelochemicals, however it can be assumed that where seed rates are higher, seedlings are more likely to be placed closer in the seedbed and thus are more likely to be affected by autotoxicity. The allelopathic effects of wheat straw will be discussed in more detail in the next chapter.

2.2 Abiotic factors

2.2.1 The Soil Climate

2.2.1.1 Oxygen availability and waterlogging

Poor germination in soils at or near saturation has been related to thick water films reducing oxygen diffusion to the seeds and seedlings (Milthorpe and Moorby, 1974). It has been suggested that a critical quantity of O_2 must be consumed by the seed in order to reach germination. Similar to the critical seed water content (Richard and Guerif, 1988) oxygen diffusion into the seed is essential for respiration in all biochemically active cells during seedling growth both before and after germination has occurred. Conditions such as waterlogging and compaction that reduce oxygen availability to the seed can be expected to have a direct effect on germination and establishment reducing both the proportion of seeds that will emerge as well as the rate of emergence.

The importance of oxygen in seed germination is supported by the work of Sladdin and Lynch (1983). They tested wheat establishment under cold and wet conditions in a greenhouse using a series of seed treatments. Calcium peroxide used as one of these treatments improved emergence up to 90%, where untreated and other fungicide and calcium based seed treatments averaged between 10% and 30% emergence. Calcium peroxide slowly decomposes on wetting to produce molecular oxygen and CaO_2. The improved emergence was attributed primarily to this supply of oxygen to the germinating seed. The neutralisation of toxins and anti-microbial effects of calcium peroxide was also cited as a possible contributory factor. Although this shows the benefits in terms of establishment that oxygen may have under adverse conditions, to be effective a seed dressing amounting to at least 25% of the seed weight is required. This renders the treatment commercially unviable under current UK economic conditions. Also tests of calcium peroxide under field conditions, on free draining and waterlogged soil, have proved to be less consistent than the laboratory effects, only improving emergence to a small extent (Thompson et al, 1983)

Excess water also affects seedlings and early plant growth by limiting aerobic respiration. Cannell et al. (1980) found that 16 days of waterlogging after germination but before emergence killed all seedlings and 6 days of waterlogging depressed plant populations to 12% of controls on clay soil and 38% of controls on sandy soils. The poor emergence and high seed/seedling losses which arose from sowings in November and December 2000 appeared to be associated with this type of effect, undoubtedly exacerbated by low temperatures resulting in slow growth processes within the germinating seed and slugs (Shepherd 2003).

2.2.1.2 Soil water potential and seed-soil contact

In many parts of the world, germination and emergence is more affected by soil moisture than any other factor. Although UK conditions, particularly in autumn, are not associated with the extreme low soil moisture contents that are seen in some cereal growing areas, changes in agricultural practice and climate may result in soil moisture becoming more limiting under UK conditions. Recent shifts in practice towards earlier sowings to improve the timeliness of autumn operations mean that seeds are being planted into soils that are likely to have a lower soil moisture content. Proposed climate change scenarios may also act as a contributory factor. These suggest a gradual movement towards lower summer rainfall and warmer temperatures, with temperature possibly increasing by as much as 1.5^0C, along side 4% reduction in summer rainfall by 2020 (Hulme and Jenkins 1998). If these predictions are accurate, drier autumn soils and poor early season germination and establishment may be more common.

For germination to occur, it has been shown that a critical seed moisture content must be achieved (Bruckler 1983). A degree of seed-soil contact is also required to facilitate water movement into the seed, however excessive contact may prevent adequate aeration. The ease with which water moves into the seed is determined largely by the seed-soil contact, which in turn is affected by the soil aggregate size distribution of the seedbed.
Bouaziz and Bruckler (1989a) took a fundamental approach to the process of water imbibition and early growth, describing plant emergence by separating the process down into 3 stages, imbibition and germination, root and seedling growth, and seedling emergence. They proposed and tested a model that was originally developed for maize seeds (Bruckler 1983), on wheat, The model suggested that the rate of imbibition was dependent on the degree of seed-soil contact and hence the proportion of water being transferred in the liquid and vapour form, taking into account both the vapour pressure and water potential differences between the seed and the soil.

The model assumed:

- The oxygen diffusion rate was a non-limiting factor.
- Water transfer occurs from the soil, to the seed through a thin layer, with specific water transfer properties, in both the liquid and vapour phases.
- That water potential gradients in the soil surrounding the seed are disregarded.
- The seed and soil water potentials depend on the seed and soil water contents respectively.
- Water flows into the seed from the liquid and vapour phases can be additive.

Through both laboratory and field studies (Bouaziz and Bruckler, 1989a&b) they concluded that the critical seed water content for germination was approximately 0.27kg kg^{-1}. Seed imbibition can occur in both the liquid and vapour phase, and soil water potential was found not to limit the rate of imbibition and germination when between 0 to –0.9 MPa. This result concurs with Lindstrom et al. (1976). Below –0.9 Mpa and above approximately –3 Mpa, germination occurred but at a lesser rate to the non-limiting domain. Below –3 MPa the imbibition process occurred until a constant seed water content was achieved, which remained constant but below the level required for germination, if the external water potential remained constant. Thus at such soil water potentials, the limiting effect on imbibition makes germination impossible. Whether imbibition occurs via vapour or liquid transfer into the seed does not affect the possibility of germination or the maximum water content, but influences the rate of imbibition, with liquid imbibition being much faster (Figure 5).

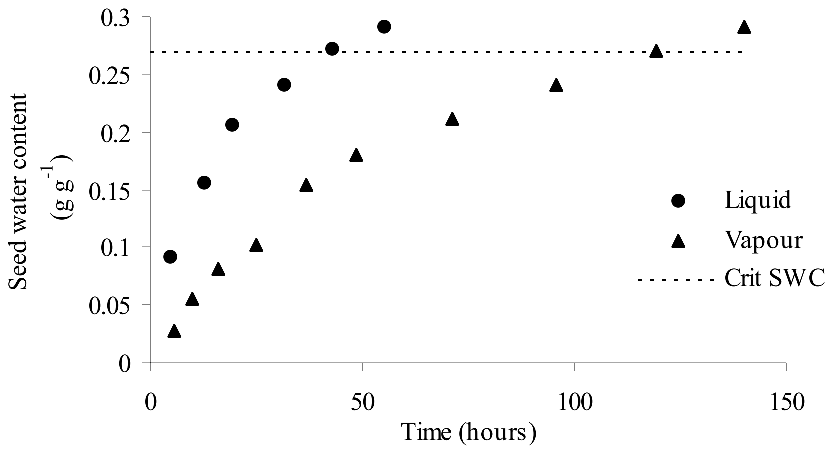

Figure 2.2 Measured wheat seed imbibition for liquid and vapour phases in the laboratory, at a water/vapour potential of Zero. Adapted from Bouaziz and Bruckler (1989a). Crit SWC refers to the critical Seed water content required for germination to occur.

Bouaziz and Bruckler (1989a) found the changes to the soil water potential affected both the rate and end point of water uptake by the seed (when below –3 MPa). The final seed water content achieved was, however, the same irrespective of the type of water transfer, and the relationship between the two lines was always similar with imbibition being quicker in the liquid phase.

Increasing the seed-soil contact, using light rollers or press wheels increases the proportion of imbibition that occurs via the liquid phase, and hence the overall speed of imbibition (figure 2.2). However, excessive pressure can lead to compaction of the seedbed, which may delay germination by reducing oxygen availability (Dexter, 1988).

The effect of soil water potentials also influences seedling growth and development. Bouaziz and Bruckler (1989b) found that as with germination, greater negative water potentials increased the time taken to emerge, but not the final % emergence in the range between –0.02 and –1.31MPa. They also found that seminal root elongation rate in wheat and final length were decreased much more than shoot elongation once soils dried to soil water potentials of -0.39 MPa or lower.

There is some evidence that delays in germination and establishment in the field may reduce seedling and plant vigour. Kirby et al (1998) investigated plant growth over a range of sowing dates from early September through to December on three sites. On various occasions, low rainfall amounts early in the planting season led to long thermal times to emergence, low plant populations and erratic seedling emergence. Plants that emerged from these sowings, also appear to show some permanent damage or loss of vigour, showing lower levels of biomass right through to harvest, than later plantings even after plant population effects had been accounted for.

2.2.2 Planting depth

Some authors have sought to attribute emergence failure to the depletion of seed reserves prior to emergence, implying that larger seeds will be more capable of emergence from deep sowings (Gan et al, 1992). Bouaziz and Hicks (1990) undertook a comprehensive analysis of wheat seed reserve consumption. Using seed with a seed weight of 46.3 ±2 mg they showed that wheat seedlings maintained in darkness on filter paper grew to 90 mm, with 50% of the seed weight remaining. Extrapolating from this they predicted that seedlings can grow to 158 mm before completely exhausting seed reserves. This suggests that poor wheat stands are not due to depletion of the seed reserves, but probably to other characteristics such as coleoptile length, soil surface mechanical resistance, soil moisture content, or, as in the case of waterlogged soils, a lack of available oxygen for respiration.

Work by Kirby (1993) has shown coleoptile length can vary considerably. Wheat was planted over a range of sowing depths on a sandy loam soil. Results indicated that establishment was not significantly affected by sowing depth in the range 23 to 83 mm. At greater depths the number of emerged seedlings gradually declined down to 6% at 143 mm (Figure 2.3A). This is consistent with other reports (Anderson et al., 1991). It appears that as sowing depth increases so too does coleoptile length until this reaches its maximum at around 70 mm (figure 2.3B). Thus, only if the coleoptile did not penetrate or come near to the soil surface, was seedling establishment affected. At depths greater than 70 mm, the leaf emerged from the coleoptile pore beneath the soil surface. Although leaf 1 is morphologically better adapted for growing through soil than the other leaves, it is less effective than the coleoptile, and at depths greater than 83 mm the growth of the leaf in some parts was deflected by the resistance of the soil and did not emerge above the soil surface. Growth of the sub-crown internodes commenced when leaf 1 was about half fully elongated, which was too late to prevent deleterious effects on establishment of sub surface leaf emergence. At the 8 mm nominal depth some seeds were almost at the soil surface and possibly suffered from drying at times, which reduced establishment.

More recent work by Mahdi et al. (1998) supports the negative effects of deep sowings on establishment. They found that using 4 sowing depths 3, 6, 9, and 12 cm the 6 cm depth was optimal. Final emergence and seedling vigour was reduced by deeper sowings. Sowing at 3 cm did on occasion give equally good establishment, however under dry conditions the 6 cm sowing gave more consistent results, in agreement with previous work.

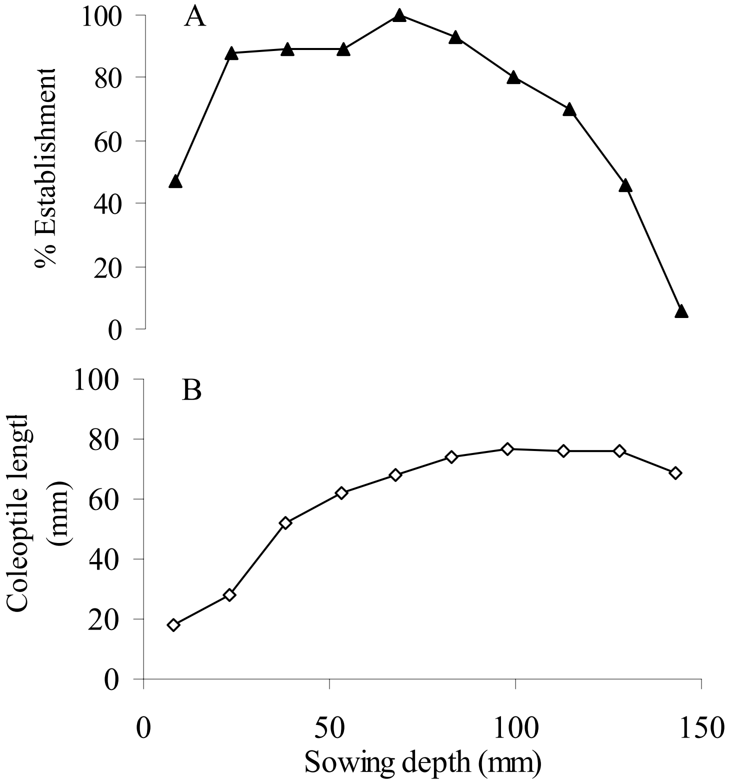

Figure 2.3 (A) The mean establishment of wheat, and (B) the final length of the coleoptile at each sowing depth. (Adapted from Kirby 1993).

2.2.3 Temperature

Numerous studies have investigated the effects of temperature on imbibition and seedling growth and germination (Bouaziz and Bruckler, 1989c; Blacklow, 1972). It is widely understood for wheat that germination can occur between 4 and 37^{O}C, with 20 - 25^{O}C seen as the optimum (Evans et al., 1975). During imbibition, temperature in part affects the rate of water uptake through the influence of water temperature on its viscosity. After the seed has become physiologically active, temperature affects the kinetics of germination by controlling the rate of the biochemical reactions in the seed.

Temperature has also been shown to affect the rate of seedling emergence in wheat. Lindstrom (1976) established a clear relationship between temperature and rate of emergence. Working in the northwest USA, he monitored emergence over a range of soil moisture conditions and a range of sowing dates, beginning in July and continuing through to October. Seeds were deep planted to a depth of between 8 cm and 12 cm. This showed that where soil moisture was least limiting, and soil temperatures were between 3 and 30^{0}C, there was a clear relationship between emergence and temperature, in winter wheat (Figure 2.4).

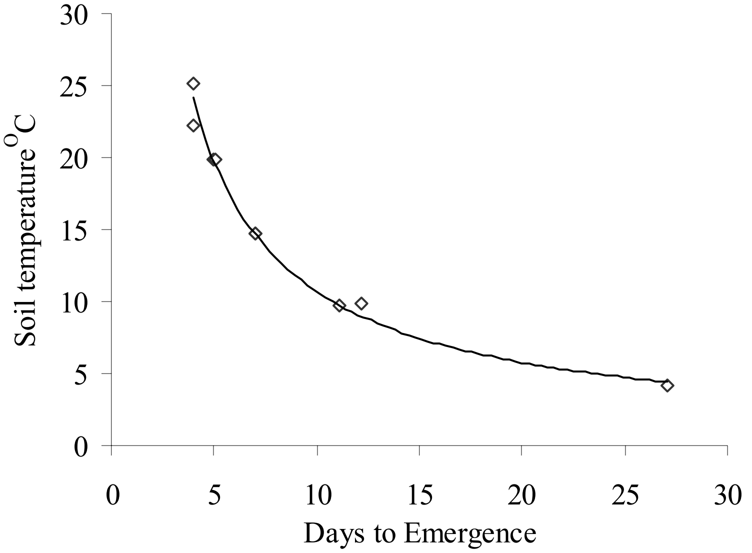

Figure 2.4 The effect of soil temperature on the speed of emergence in winter wheat cultivars Nugaines and McCall. (adapted from Lindstrom et al., 1976).

Under field conditions it might be expected that dark coloured soils are warmer than light soils as they will absorb more of the solar radiation. Soil temperatures are also linked to soil moisture. In summer, high soil water content can buffer soil temperature, preventing any major fluctuations. Thus where high soil temperatures are observed this is likely to be associated with low soil moisture. In the field simply using temperature as an indicator of establishment is inappropriate, especially at the upper end of the soil temperature range.

2.2.4 The Soil Structure

2.2.4.1 Soil impedance

As discussed earlier good seed soil contact can aid water uptake by the seed and hasten the onset of germination and emergence. However for roots and coleoptiles to elongate, the soil strength should not be excessive. Soil compaction increases the bulk density, eliminates many of the large diameter transmission pores that serve for drainage of water, limiting the exchange of gases, especially oxygen, between atmosphere and soil, as well as impeding root penetration (Cannell, 1983). In addition, where soil structure is interrupted by natural (or induced) pans, or in naturally structureless soils dominated by fine sand or silt size particles, few transmission pores are present (Cannell, 1983). These naturally structureless soils may also form surface crusts. Crusts generally form as a result of rainfall followed by drought on these soil types and is a special case of soil impedance. Seedling response depends mainly on crust water content, crack pattern, and seedling size and shape. If the crust is thin, seedlings may break the crust, because there is no resistance in the atmosphere above it. Under UK conditions crusting is viewed as more problematic in spring crops where gradually increasing temperatures increase the risk of damaging levels of soil surface drying following post sowing rainfall. Timely irrigation of high value spring planted vegetable crops has been shown to benefit establishment by reducing soil strength in carrot seedlings (Finch-Savage, 1990). This is less likely to be necessary for spring cereals as monocotyledons usually have a sharp shape and are better able to penetrate crusts than dicotyledon species, which mostly have a hook shape (Goyal et al., 1982). The availability of irrigation facilities as well as treatment costs generally makes this uneconomic in cereal crops.

2.2.4.2 Aggregate size

It has been suggested that the optimum seedbed is composed of aggregates in the range of 1-5 mm diameter with up to 15% of finer material (<250µm) (Russell, 1973). Bouaziz and Bruckler (1989c) showed that where fine and coarse soil structures were observed (corresponding to 5% and 25% of aggregates <3 cm in diameter), the coarse seedbed had consistently higher levels of germinated non-emerged seedlings, than the finer seedbed over three artificially imposed rainfall patterns. This is in agreement with numerous field observations eg. Fenech and Papy (1977). Nasr et al. (1995) linked increased aggregate size as well as bulk density to reductions in the rate and final % establishment. The effect of aggregate size was associated with the increased path length from the seed to the soil surface. The effects of bulk density were attributed to changes in the volume and continuity of pores in the seedbed. Aggregate size may not just increase the path length Wheat seedlings have been shown to exert a maximum force of about 25-30 g against a non penetrable obstacle. This corresponds to an average pressure of 170Kpa. Assuming a spherical clod shape with a bulk density of 1.7g cm^{-3}, wheat seedlings could successfully emerge from a seedbed with clods less than 30mm in diameter (Bouaziz et al., 1990) (Figure 2.5).

These results suggest that where seed soil contact is adequate for germination, the physical conditions of the seedbed will affect the rate and final level of establishment achieved.

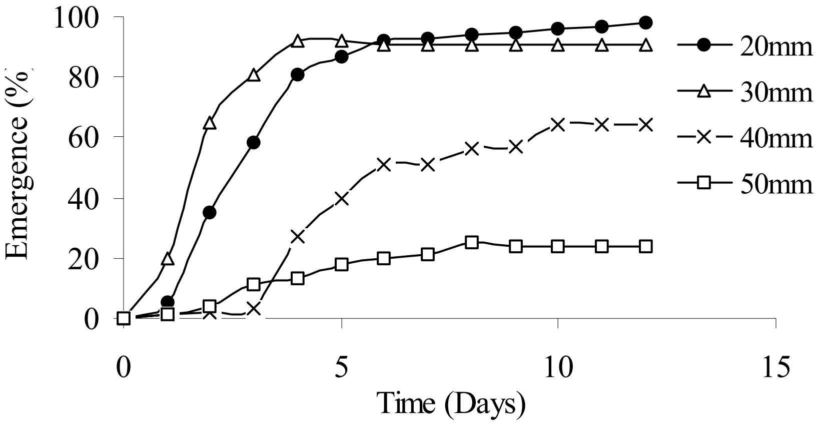

Figure 2.5 Emergence patterns for wheat seedlings growing under soil blocks of different sizes and weights (Bouaziz et al., 1990).

2.2.4.3 Cultivations and soil type

There is a great need to be able to predict the effects of factors such as soil type, seedbed preparation and sowing techniques on crop establishment. Changes in machinery are costly to the grower, but their effects on establishment are not easy to predict. Timely tillage can alleviate soil compaction, however there is much evidence that repeated tillage can cause a deterioration of soil structure (Low, 1972: Greenland, 1977), nevertheless, not all soils are appropriate for direct drilling. In poorly drained soils, direct drilling can cause the walls of the drill slits to smear restricting oxygen diffusion to the seed (Lynch, Harper and Sladdin, 1981).

The suitability of land for direct drilling does appear to vary between soil types. On heavy clay soils in the UK (which represent 45% of the cereal growing area), provided compaction has not occurred at harvest, a degree of self structuring in the upper 2-3 cm at the end of the summer can provide ideal conditions for germination (Cannell, 1982). Soils where direct drilling has occurred also have more continuous soil pores formed by cracking in summer and by earthworms, and may aid water infiltration and root elongation compared to land cultivated with the plough. (Goss et al. 1978). On UK silty loam soils experiments indicate that although the soil surface is initially unsuitable for direct sowing, where it has been practised for a number of years establishment and growth improved. This effect has been associated with higher organic matter and more stable aggregates in the top 2.5cm with direct drilling. (Douglas and Goss, 1982).

In several countries coarse textured sandy soils have been the amongst the least successful for direct drilling, this has been noted in Britain and Australia (Cannell, 1983). On a loamy sand in western Australia, in the fourth consecutive year of a long term tillage experiment, after disc ploughing to 8cm, soil strength was less than after direct drilling, root extension was faster and dry matter production greater, even from the early establishment stage (Hamblin et al. 1982).

The best use of reduced cultivations also appears to be dependent on soil type in a similar way. On sands, light loams, light and medium silts and peaty soils, it has been suggested that using a plough and press is the most appropriate form of tillage whereas under dry conditions on medium loams and clays shallow tillage is more suitable, unless weed, trash or drainage problems are evident (Davies 1988).

2.2.4.4 Straw residues

Straw residues may have direct effects on seedling establishment. In the past, straw residues have been noted to cause mechanical problems at drilling (Cannell 1983), and wheat straw has been shown to release allelopathic chemicals capable of affecting seedling growth. Alam (1990) reported that the germination and growth of wheat were significantly decreased by aqueous straw extract of the same variety. Other work in Australia has shown that wheat autotoxicity varies with variety (Kimber 1967) for example found that cv. Gabo exhibited a stronger inhibitory effect than cv. Insignia. Straw extracts of cv. Gabo and cv. Insignia inhibited root growth in cv. Gabo wheat seedlings by 27% and 4% and shoot growth by 43% and 27% respectively. It appears the bulk of research on allelopathy and autotoxicity has been conducted in Australia, Canada and America. The degree of straw decomposition prior to the next crop may well affect the allelopathic responses of the next crop. The loss of allelopathic activity after a period of straw decomposition has been reported (Guenzi 1967). An adequate time gap between straw decomposition and crop sowing seems to be a pre-requisite for the healthy growth of the next crop. The effects of take all on second wheats and subsequent wheat crops in the UK generally precludes early sowing where 2nd or non-first wheat is being sown. High summer rainfall in the UK compared to Canada, America and Australia, is also likely to increase rates of straw decomposition, reducing the importance of autotoxicity effects. Recent trends towards earlier 2nd wheat sowings (through the availability of seed treatments to reduce the effects of take-all), along with climate change models predicted drier summer conditions (Hulme and Jenkins, 1998), and increased interest in minimum tillage techniques, all indicate that autotoxicity may become more important.

The presence of straw residues around the seed is thought to also provide a carbon source for micro-organisms that produce toxic anaerobic metabolites, (Lynch, 1980). This can only occur under anaerobic conditions, and as such may be a contributory factor for poor establishment under very wet seedbed conditions.

Technological improvements in combine straw chopper design, combined with generally shorter straw varieties, have gone some way towards alleviating the negative effects of straw residues. Finely chopped straw residues, spread evenly over the soil, has the effect of both reducing mechanical impedance at sowing, and increasing the speed of straw decomposition, by increasing the surface area in contact with the soil (Fruit et al 1999).

2.2.5 Overwinter survival

Previous research on plant populations (Spink et al. 2000) specified the minimum spring plant population needed to maximise crop gross margin. Winter kill directly affects on spring plant populations, and as such its prediction or avoidance could be significant in maximising margins, wherever it is likely to occur.

It is apparent that cereals differ in their winter hardiness. Winter rye and winter wheat are considered the most winter hardy. In the past Winter barley and more especially winter oats have both been shown to be susceptible to overwinter plant loss under UK conditions (Wibberley, 1989), More recently, a succession of milder winters combined with breeding and selection for hardier Oat varieties appear to have reduced the incidence of frost damage and winter kill (J. Valentine, pers. com).

Despite its perceived importance within the industry, there has been very little work conducted specifically on winter kill in the UK, although there are several factors that have been associated with it.

Waterlogging has been shown to prevent oxygen diffusion to respiring plant tissues. Although most emerging seeds and plants can survive short periods, if soils are waterlogged for an extended period plant death will result (Cannell et al., 1980).
Frost heave can occur where soil surface structure is such that when ground frosts occur the soil particles freeze together and expand damaging the shoots of protruding seedlings. This is most common on light structureless soils, or where more full bodied soils are over cultivated leaving an excess of fine surface tilth.

Experiments at Aberdeen have indicated that low seed rates may also be more susceptible to winter kill. Where plots were sown at 320 seeds/m2, winter kill was 17%, however at 40 and 80 seeds/m2 this increased to over 35%, probably due to less insulation of the soil surface (J. Spink, pers comm.).

Shallow sowings are believed to make plants more vulnerable to frost damage, since the roots the most frost sensitive part of the plant are nearer the surface and more exposed to the ground frost. Sowing date and pre-winter growth have also been linked to over winter plant survival. Adak 1993, studied the effects of growth and development on winter hardiness in barley in field experiments in Turkey. Six varieties were tested over two years. Positive and significant relationships were found between cold hardiness and crown depth, root length, dry crown weight and number of tillers. This corresponds to the practical guidelines for sowings under UK conditions. These indicate that winter barley and winter oats should be sown in good time to ensure adequate early rooting (Wibberley, 1989).

2.3 Biotic Factors

2.3.1 *Crop Pests*

2.3.1.1 Slugs

Slugs are a major pest of arable crops and often cause serious damage to winter cereals at establishment. In wheat damage is either in the form of damage to the seed in the form of grain hollowing, preventing successful seedling germination, or grazing of the shoot pre-mergence and/or the leaves of newly emerged plants reducing the rates of plant growth and survival. Slugs can survive and eat all crops within the rotation. In previous years considerable damage has only occurred in late October and November on cereals where late drilling caused slow plant growth in cobbly seedbeds.

Several different types can affect winter cereals, the most common being the grey field slug (*Deroceras reticulatum*). Activity has been found to correlate with both temperature (Webley, 1964) and humidity (Baker 1973). Slugs have a variable life cycle with opportunistic breeding to allow them to take advantage of any favourable conditions that may occur. Wet and humid summers are likely to cause increases in slug populations, where as prolonged dry conditions should restrict breeding activity and survival. Although cool conditions appear to negatively affect most slug species, Mellanby (1961) showed that even at a temperature of 0.8^{o}C, Deroceras reticulatum fed very actively on young shoots of wheat.

Molluscicides have been shown to at best only kill about 50% of the slug population (Glen *et al.* 1991), possibly because many slugs are not surface active during the period when the molluscicide is effective. Cultural techniques found to control damage include the preparation of fine firm seedbeds, and deeper drilling in cobbly seedbeds (Glen et al 1992). Slugs have also been linked to rotational position with populations shown to have a tendency to build up in oilseed rape crops (Glen 1989). Two recent developments include an investigation of the potential for using slug parasitic nematodes (Glen and Wilson, 1997), and transgenic plants that produce proteinase inhibitors (Walker et al. 1999). These may have potential for future use but expense and availability currently prevent them from being viable strategies. There is also some evidence to suggest wheat seeds that have been treated with the insecticide imidacloprid (Secur) are protected from slug damage.

2.3.1.2 Frit fly (*Oscinella frit)*

In spring cereals of frit fly adult is on the wing in May and will lay eggs on newly emerged crops of oats and maize. The larvae feed in the shoots causing typical deadheart symptoms. Later in the season frit fly may affect autumn establishment flying in and laying eggs on cereal volunteers and grasses, larvae may also transfer from ploughed down grass, causing classic ley pest attacks. The larvae enter cereal shoots at the top and complete their development in a single cereal shoot (Oakley 2000).

Attacks from the spring generation are favoured by late sowing so that crops are at the most vulnerable at the one to two leaf unfurled growth stages (GS 1.1 – 1,2) when egg laying is at its peak in May (Linblad & Sigvald, 1999). Autumn damage is dependent on the size and timing of the third generation of adults, and the suitability of soil conditions for the migration of larvae from the ploughed down sward to the new crop. Warm and damp soil conditions favour larval migration in the soil. After oats, ryegrass is the preferred host for frit fly, with Italian ryegrass more favoured than perennial. The parasitoids of frit fly are slow to establish in newly sown leys, but tend to reduce numbers from the third year onwards. These factors combine to give peak numbers of larvae at the end of the second year of Italian ryegrass leys, which are often ploughed down at this stage. Therefore winter cereal crops after two-year old Italian ryegrass leys are considered to be the most vulnerable.

Early sowing of spring oats is advised to reduce the impact of damage, with a target of the crop reaching GS 13 by mid-May when egg laying commences. Early ploughing is recommended for the reduction of damage in the autumn, with a minimum interval of five weeks between ploughing and sowing being advised. Where this interval can not be obtained sowing immediately after ploughing is the next best alternative so that the crop is well established by the time the larvae migrate.

2.3.1.3 Leatherjackets *(Tipula paludosa, T. oleracea)*

Leatherjackets are the larvae of the crane flies *Tipula paludosa* and *T. oleracea*.
The larvae feed at the soil surface at night cutting through cereal shoots. When the grass is first ploughed the larvae remain feeding on the buried sward for several weeks and migrate to feed at the soil surface. Leatherjacket attacks tend to appear a few weeks after crops are sown and can develop rapidly, often causing considerable damage before detection.
Adult *T. paludosa* scatter their eggs over grassland in the late summer, favouring damp swards of moderate height. The eggs hatch after about a month. Eggs and young larvae are very susceptible to desiccation, wet September weather thus favours survival of

higher numbers. As each female lays around 300 eggs the degree of mortality is of great importance and can result in large fluctuations in incidence from year to year.

The larvae feed through the winter and spring before pupating in May. They feed whenever the minimum night temperature remains above 5°C so that winter crops may be progressively thinned throughout the winter. Spring-sown crops may suffer more rapid plant loss, as the leatherjackets are much larger by the spring and can feed at an alarming rate.

T. oleracea adults are active in early summer and usually lay their eggs in damp situations, hence the attraction to nursery stock grown on sand beds or other forms of regular irrigation. Low numbers may be found in arable fields and Coll & Blackshaw (1996) have demonstrated that in NE Scotland adults emerging in oilseed rape fields are unable to escape and remain there to lay their eggs. The larvae feed through the summer and are nearly mature by the time that cereal crops are sown in the autumn when they can cause rapid plant loss. The problem does not seem to occur elsewhere in the UK where the timing of adult activity or the distribution may vary.

Ploughing up of grass by early August before sowing winter cereals prevents problems. Early ploughing is also advised for spring cereals, together with timely sowing in a well consolidated seed bed. Alternatively it has been suggested that grassland could be rolled to disrupt adult emergence, if the emergence of the adults could be accurately predicted (Kell & Blackshaw, 1988).

2.3.1.4 Wheat bulb fly *(Delia coarctata)*

The wheat bulb fly is mainly a pest of the arable areas in the east of England and Scotland, and affects over winter plant survival. Incidence fluctuates considerably from year to year according to late summer rainfall (Young & Cochrane 1993). In recent years, the pest has increased in importance in Lancashire, and this increase and sporadic outbreaks in the south and west of England are probably the result of the adverse effects of set-aside (Young & Ellis 1996; Young *et al.* 1994).

The adult wheat bulb fly lay eggs in late July on bare soil, favouring that which is newly turned (Raw 1955), and on bare soil exposed beneath the canopy of crops such as sugar beet, potatoes and onions. The eggs undergo a period of diapause and the larvae hatch from December to the end of March. The larvae migrate to the soil surface and seek a host plant secreting an arrestant exudate (Long 1958; Greenway *et al.*, 1976). Wheat, barley and rye plants are all attacked as are a range of grasses (Raw & Stokes, 1958), The larvae feed for a period in their first shoot and moult through to the third instar before moving on to feed in two or more further shoots in April before pupating in the soil at the end of May (Young & Ellis, 1996). The damage caused is at its most severe with late November to February sown crops still at the single tiller stage (GS 21) at the time of attack. Here the plants are killed outright, often before the larvae are sufficiently mature to reach another tiller, so that there is little of the second phase of damage. Tillered crops suffer less damage unless numbers of larvae are high. Larvae tend to attack the outermost secondary tillers and leave the main shoot unharmed. Yield losses of up to about 4 tonnes/ha have been recorded following severe damage (Young & Ellis, 1996).

Cold winters check plant growth and increase the survival of wheat bulb fly eggs by deterring predation and disease. The greatest risk of crop damage therefore comes when a cold winter follows a favourable summer for egg laying, especially if cool, wet weather in the autumn delays drilling (Young & Ellis 1996).

Early sowing reduces the impact of damage, as more tillers are available when the larvae invade, reducing the loss of plants (Young and Ellis 1996), The re-arrangement of a rotation to follow egg laying situations with non-host crops such as oilseed rape or oats could provide a simple solution.

2.3.1.5 Wireworm *(Agriotes lineatus, Agriotes obscurus)*

Wireworms are the larval stages of click beetles, the most important agricultural pests being *Agriotes lineatus* and *A. obscurus*. Although other species may occasionally occur, they rarely reach damaging levels. The larval stage lasts for 4 – 5 years and classically cereal crops following grass may be attacked in the first 2 – 3 years after ploughing out pasture. Wireworm larvae are quite polyphagous, feeding on a range of plant material and detritus.

The switch to winter cereal cropping and the introduction of set-aside have allowed the development of damaging wireworm populations in arable rotations and the incidence of such damage has progressively increased through the last decade.

The larvae feed within the soil biting into cereal shoots, which develop the classic 'deadheart' symptom. A circular entry hole with tattered edges is typical of wireworm damage, but is similar to that caused by some other stem-boring pests. Wireworms tend to be most active in the spring and autumn and to enter quiescent phases in the summer and winter.

Numbers found in permanent pasture fields tend to increase for the first 15 years after sowing after which populations tend to stabilise (Parker & Seeney, 1997). Numbers differ considerably between permanent pasture fields, possibly due to differences in initial colonisation. Attacks are favoured when permanent pasture is ploughed up and in crop rotations comprising of all winter cereal or cereals and set-aside. Crops are at their most vulnerable when at the single shoot stage and late sowing and slow growth may exacerbate problems.

The eggs and young larvae are vulnerable to desiccation, and spring ploughing followed by a summer fallow has been recommended as a control measure. A spring sown crop can provide a similarly unfavourable environment, but most would not be recommended in the presence of high numbers of wireworms due to their vulnerability to damage. Linseed, flax and peas are reputedly resistant to damage and could have a role to play in a rotational control approach.

2.3.2 Crop diseases

2.3.2.1 Fusarium (seedling blight)

Fourteen or so species of *Fusarium* have been isolated from wheat crops in the UK. In recent surveys *Microdochium nivale* previously known as *Fusarium nivale* was recorded as the most predominant. (Locke et al 1987, Jones 1994). *Microdochium nivale* can cause a failure to germinate (Humphreys 1995), pre-emergence and post-emergence death of seedlings, as well as foot rot and ear infection in winter sown cereals (Cristani

1992). Barley, Oats and Rye can also be severely affected by fusarium seedling blight, much like wheat.

The presence of high levels of *Microdochium nivale* on seed has been directly linked to poor plant establishment. Humphreys et al (1995) tested nine wheat varieties with *M. nivale* infection levels ranging from 6%-79%. Plant establishment in the field also varied significantly between varieties (26%-69%), and the correlation between percentage infection and plant establishment in the field was r= -0.971; P<0.001. In this work they also tested germination on moist pleated filter paper. This revealed that the percentage of abnormal germination, (failure to germinate or the production of abnormal seedlings) varied from 4%-54% between varieties. Percentage abnormal germination was found to be significantly correlated with both establishment in the field (r=-0.900; P,0.001) and with % *M. nivale* levels detected on seed (r= +0.930; P<0.001).

The level of seed-borne infection is almost entirely due to weather conditions following ear emergence and subsequent flowering in the parent crop. Thus, in high-risk years the level of seed-borne infection is likely to be equally high in certified seed as it is in home-saved seed.

Because the *Fusarium* species are carried within the seed coat, rather than superficially on the seed surface, they are not easily controlled by surface-acting fungicides. All of the current seed treatment fungicides do though give reasonable control.

2.3.2.2 Septoria seedling blight *(Stagonospora nodorum)*

Although more usually associated with necrotic blotching of leaves and glumes, *S. nodorum* can cause pre- or post-emergence seedling blight in cool wet soils.

Like the *Fusarium* species, *Stagonospora nodorum* can survive between crops either on seed or on plant debris. While trash-borne inoculum is usually more important in initiating the later phases of the disease (leaf spot and glume blotch), fungus carried on the seed is more likely to be responsible for septoria seedling blight. Seed treatment reduces the risk of septoria seedling blight.

3 REVIEW OF DATA SETS

Data from a wide range of UK experiments has been reviewed to investigate how cereal establishment is affected by soil type, method of cultivation, seed bed tilth, meteorological conditions prior to and post drilling and a range of other factors.

A large number of field experiments have been run in the past by ADAS and others where it is possible to determine the number of seeds sown, the resultant plant populations and the climatic conditions prior to and after sowing. For the purpose of this review, this large data resource was collected in a standard format and analysed to determine the key factors affecting establishment.

3.1 Methodology

3.1.1 Data collection

In order to produce a data set which was both robust and broad enough to allow the required analysis, experiments differing in location, soil type, sowing date and year were identified. A screening process was then necessary to ensure that experiments for inclusion contained a satisfactory depth of information, to ensure the recording of establishment was satisfactory, and information on the main factors believed to affect establishment was known.

The information requested was separated into two categories to ensure the maximum amount of useful information was gathered without excluding additional information that could provide added value. These categories were 'Essential information' and 'Useful additional information' as shown in table 3.1.

Table 3.1 Classification of information for the selection of experiments for inclusion in the database.

Essential info	**Additional info**
Seed rate preferably seeds/m^2	Previous crop
Plant populations, autumn and/or spring counts	Soil stoniness
Rainfall and temperature data, before and after sowing.	other cultivations
Location	+/- cambridge rolling
Date of Sowing	Variety
Soil texture	
Primary form of cultivation eg. Plough, disc or none.	

3.1.2 The Data entry template

The data template was designed such that information from each experiment formed one line in the spreadsheet. In many cases experiments had treatments that may have affected establishment such as sowing date, variety, cultivation, seed rate etc. Under these circumstances if treatment specific autumn or spring plant population counts had been taken, each treatment was included as a separate line on the spreadsheet. For example an experiment with 4 different cultivations treatments formed 4 individual treatment lines (records) on the spreadsheet.

The initial aim, following discussions with statisticians was to achieve around 50-80 records from each of 10 sites across the UK, to give achieve a broad data set with a total of 500 to 800 records. It was considered that such a depth of data that would allow a meaningful statistical analysis to be conducted. In total 1250 records[*] were collected from a total of 27 different sites from the south coast up to Aberdeen, covering a full range of soil types and sowing dates. Experiments from each of the last 25 years (1977-2002) were used to ensure the records encompassed a wide range of autumn environmental conditions.

Regression analysis was carried out using GENSTAT to determine the relationship between autumn and spring counts and also the importance of each of the individual factors to both autumn and spring counts. Counts were tabulated for relevant groupings of factors and means, standard errors and confidence intervals were calculated.

3.2 Results

3.2.1 Autumn and spring plant populations

Within the 1250 records, 891 had autumn plant population counts and 579 were counted in the spring. An analysis of the 220 records with both autumn and spring counts showed that their was no consistent relationship between autumn and spring counts. The two counts could therefore not be statistically combined into one establishment figure. The analysis conducted here focuses mainly on the autumn counts as the data represented the larger of the two sets, however, in some specific cases both sets are assessed. It was decided that for the purposes of the analysis those with both autumn and spring plant counts could be included in both the autumn and spring analyses.

3.2.2 Main factor effects

The influence of each factor on establishment was assessed by calculating the percentage variance it accounted for using regression analysis (Table 3.2). From this initial analysis it appeared that the factors having the largest effect on autumn establishment were the date of sowing, and the area of the country, each accounting for 25% or more of the variation. Previous cropping, soil temperature, soil texture, and the year of sowing also each appear to account for over 10% of the variance in establishment. Other factors such as soil tillage appeared to have less of a direct effect on establishment.

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[*] The complete data set is available from J Blake at ADAS Rosemaund or the HGCA on request.

Table 3.2 The percentage of variance in establishment accounted for by the factors observed.

	% Variance accounted for	
Factor	**Autumn**	**Spring**
Month (date of sowing)	28.6	2.9
Area (Region)	24.9	22.2
Previous crop	15.7	21.9
Soil Temp (10cm)	13.4	2.7
Soil Texture	11.6	4.9
Sowing year	11.4	20.1
Soil stoniness	3.3	0
Seeds/m2	1.9	5.6
Tillage		
Primary Tillage	0.2	0.6
Secondary Tillage	4.6	1.3
Tertiary Tillage	0.1	0
Rainfall		
Rain 20 days pre-sow	2.3	0
Rain 10 days pre-sow	0	3.7
Rain 5 days pre-sow	2.3	5.3
Rain 5 days post-sow	1	7.9
Rain 10 days post-sow	0.1	1.3
Rain 20 days post-sow	0.2	0

3.2.3 Effect of date of sowing.

To distinguish the major effects, and ensure the numbers of records in each category were sufficiently large to provide confidence in the results, sowing dates were categorised by half month in September and October, with a final category for those sites sown in November or later. The results indicate that the mean percentage autumn field establishment from September and early October plantings was broadly similar at between 67 and 70% (figure 3.1). For late October plantings this fell to 60% and for plantings in November or later the average establishment was below 50%.

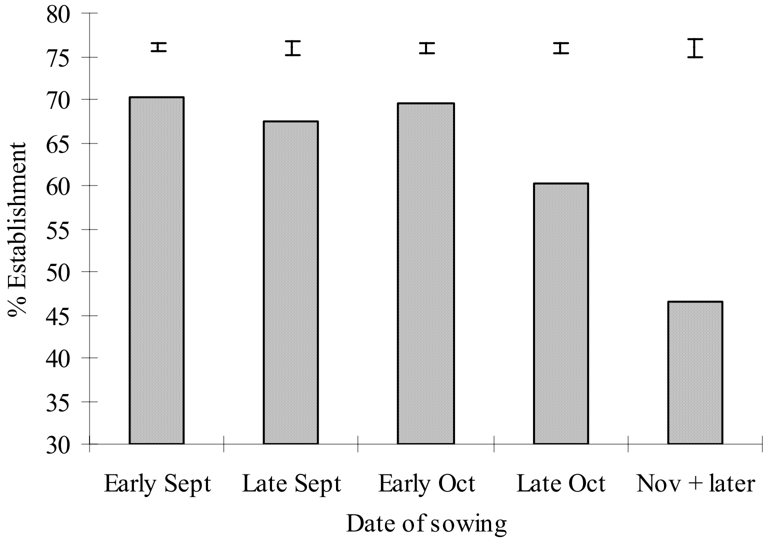

Figure 3.1 Mean autumn establishment across all sites, Error bars indicate the standard error of the mean.

An analysis of the effect of sowing date on spring establishment was also carried out. The early September category was excluded because it had less than 5 records with spring plant population counts. There was a higher level of variance around the means compared to autumn counts. Several reasons can be postulated for this including: 1) variable winter kill, 2) fewer spring counts and 3) difficulty in counting plants accurately in the spring. The spring counts were, on average, 5-10% lower than the autumn counts, which is probably due to winter kill. The spring plant populations (figure 3.2) showed a similar trend to the autumn establishment pattern with a general decline in establishment with delayed sowing.

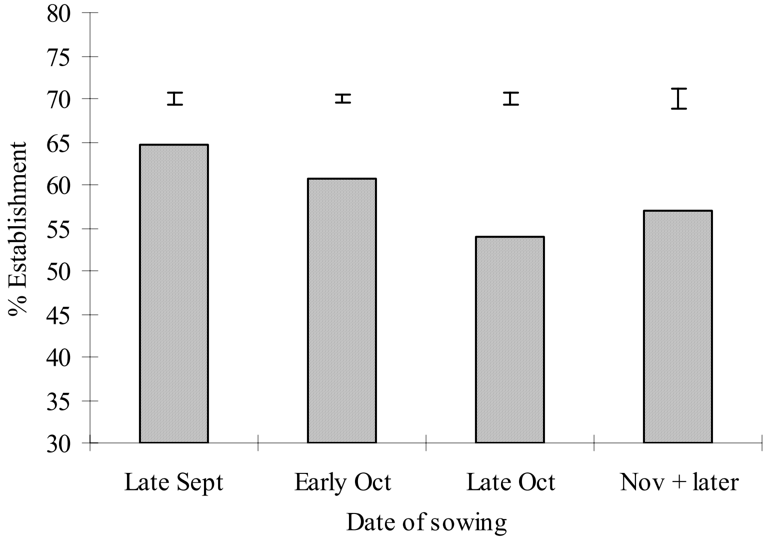

Figure 3.2 Mean Spring establishment across all sites, Error bars indicate the standard error of the mean.

Sowing date may also be used to indicate the risk of suffering a particularly poor level of establishment. Figure 3.3 shows that from an early September planting only 26% of crops established less than 60%, and only 3% had less than 40% establishment. A similar pattern is observed for both Late September and early October sowings with the only notable exception being a small increase in the number of sowings achieving less than 60% establishment. Where sowing occurred in late October and later, the percentage of cases where less than 60, 50 or 40% establishment was achieved increased, with 75% of the late sowings (November, December and January sowings) reaching less than 60% establishment, and approximately a third of these achieving less than 40% establishment (Figure 3.3)

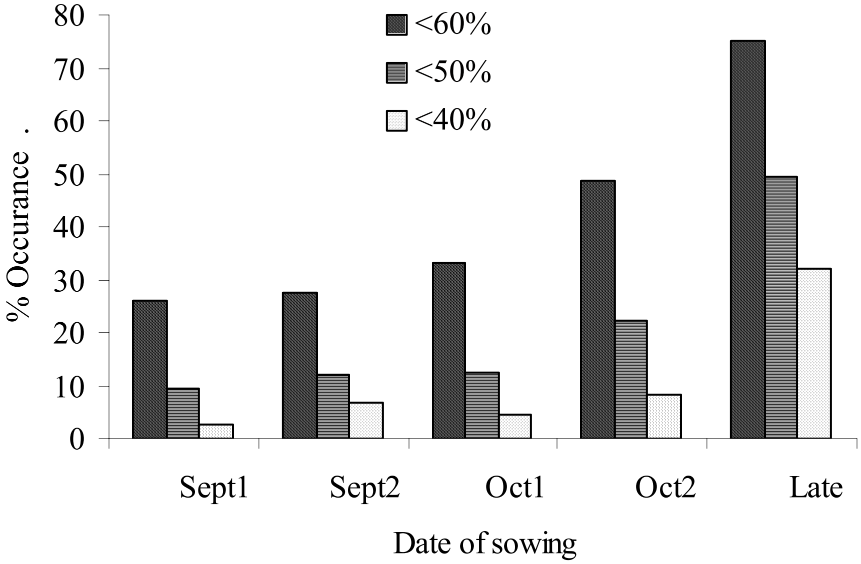

Figure 3.3 The percentage of cases where poor autumn establishment (less than 40, 50 and 60%) occurred, over a range of planting periods.

3.2.4 *Soil Temperature.*

The effect of delayed sowing on establishment may in part be related to the negative effect of temperature on the duration and probability of emergence (discussed in chapter 2). The temperature at 10 cm soil depth on the date of sowing was therefore used to investigate the direct effect of soil temperature on emergence. Data for this was taken from the nearest available meteorological station (in most cases this was on the same site as the field experiment).

As expected temperature appeared to influence establishment with the poorest establishment occurring when temperatures were at 0-4°C (figure 3.4). Establishment increased with increasing soil temperatures until soil temperatures reached 8-12°C. There was no further increase up to 16°C, but over 16°C there was a tail off in establishment. Numerous studies have shown that the optimum temperature for germination is between

20 and25°C. This difference is probably due to colder temperatures at the 10cm measurement depth compared with planting depth. Another reason may be the result of an interaction with soil moisture. All sowings where soil temperature exceeded 16°C were sown in the first half of Sept. At this time in the season the probability of seeds being planted into dry soils, and water availability limiting establishment (despite favourable temperatures) is higher than at any other time in the autumn. Evaporation rates at this time would also still be high, limiting the benefits of any rainfall, and creating a drying front that moves down the soil profile post sowing.

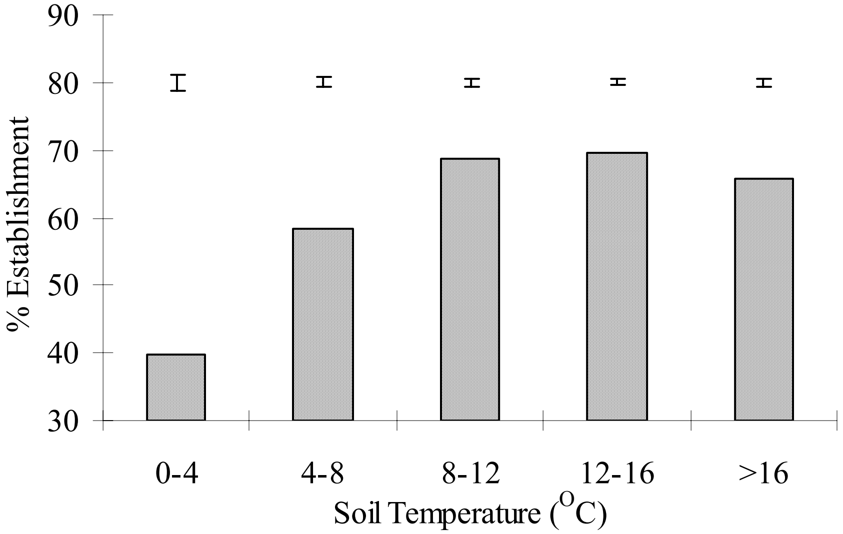

Figure 3.4 The effect of soil temperature on establishment. Error bars indicate the standard error of the mean.

At the early September sowing, soils were all above 12°C (figure 3.5A), and mean establishment was higher where soil temperatures were lower, as previously discussed this may reflect the interaction between soil moisture and soil temperature at 10 cm depth. Soils at higher moisture contents are also likely to have lower temperatures. As such, cooler soils at this time of the year (those in the 12-16 °C category figure 3.5A) may be a reflection of higher soil moisture contents.

In late September and early October plantings, average establishment was above 66% at all soil temperatures, with the exception of where soil temperature was below 8 °C in early October. This only occurred in 8.6% of the records during early October and average establishment was still above 62% (figure 3.5 C&D). As with early September sowings, the best temperature for establishment in early October is not the highest soil temperature. This again may be linked to dry soil conditions at this time (figure 3.5C).

Where soil temperatures at planting were between 8 and 12°C in late October mean establishment was over 80% (figure 3.5D). At this point in the season in the UK, water is less likely to be limiting imbibition and germination as by November soils are usually close to field capacity. Warm soil temperatures at this point in the season, would therefore be likely to result in a rapid germination and emergence.

It was only from early November onwards that soil temperatures dipped down below 4°C (figure 3.5E) resulting in very poor establishment.

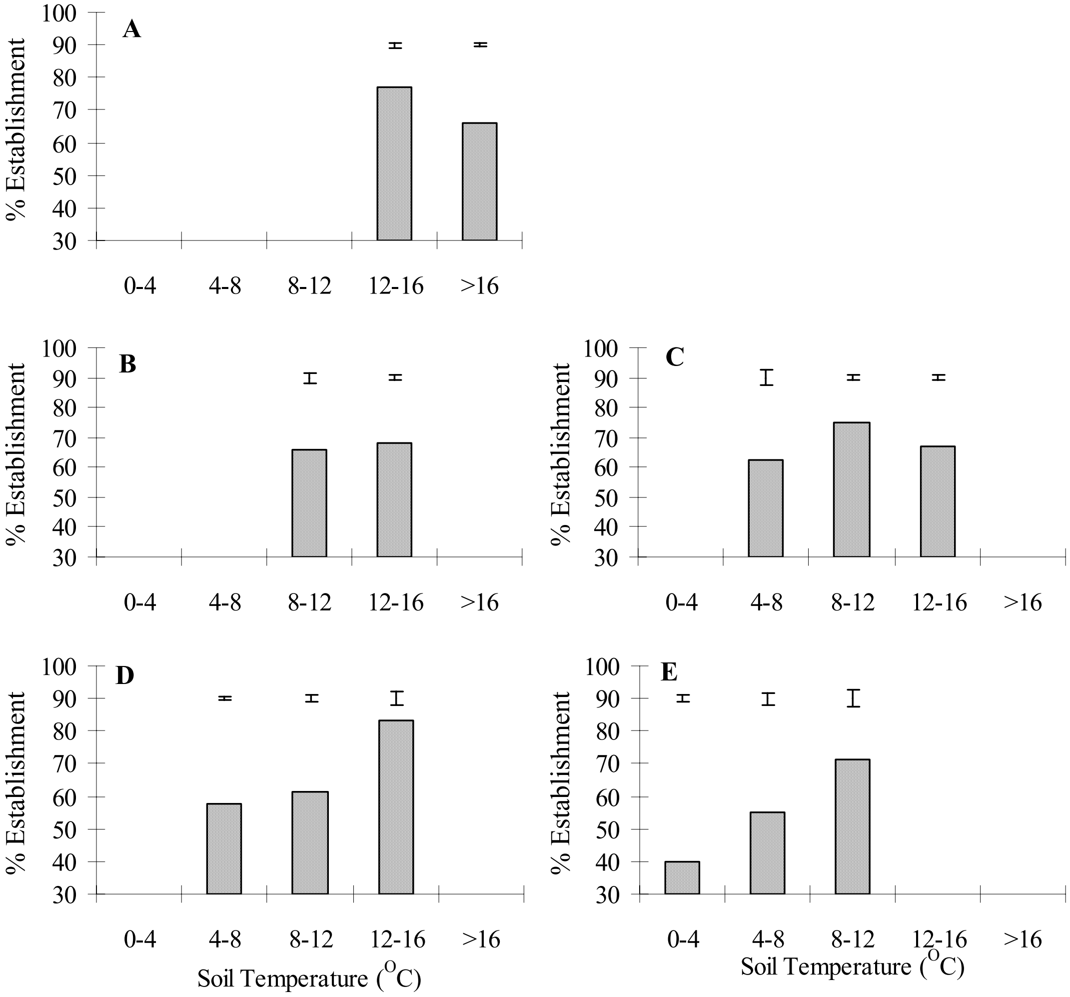

Figure 2.5 The effect of soil temperature on establishment over the range of sowing dates. Letter represent the following sowing date categories A = Early Sept, B = Late Sept, C = Early Oct, D = Late Oct and E = November or later planting. Error bars indicate the SE of the mean.

3.2.5 Rainfall

Total rainfall in the 5, 10, and 20 day periods both before and after sowing were recorded to assess the impact of rainfall on establishment. Rainfall both before and after establishment accounted for a maximum of 2.7% of the variation in autumn establishment, and 7.9% of the variance in spring establishment (table 2.1). Regression and analysis of variance statistics revealed that there is no direct relationship between any of the rainfall variables and establishment.

The effect of rainfall on establishment was also investigated over the 8-12 ^{o}C and 12-16 ^{o}C soil temperature categories, to see if there was an effect of soil moisture on establishment at higher soil temperatures (figure 3.6). Ideally here we would have used the >16^{o}C category, however there were present in insufficient numbers for an analysis of this kind.

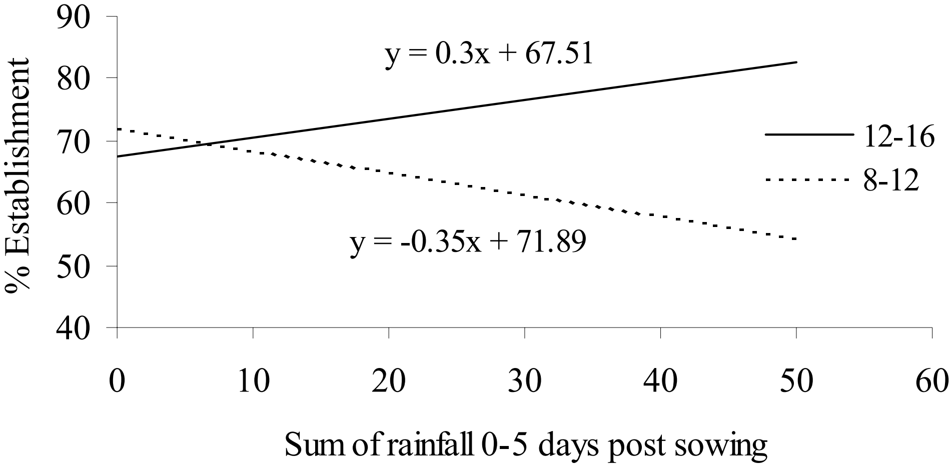

Figure 3.6 The effect of rainfall on autumn establishment at different soil temperatures. 12-16 and 8-12 represent soil temperatures (^{o}C). There were significant improvements fitting lines with independent slopes and intercept accounting for 30% of the variance in the data.

The regression analysis indicated that at lower soil temperatures increased in rainfall immediately post sowing had a negative impact on autumn establishment, however at higher soil temperatures the trend was reversed with increases in rainfall having a positive impact. In September and early October high soil temperatures are more likely to be associated with high soil moisture deficits and so germination is restricted by a lack of available water, later in the season as soil temperatures fall and soils reach field capacity, increased rainfall is more likely to cause water logging and impaired oxygen availability. Results were less consistent below 8^{o}C and above 16^{o}C in part due to the smaller sample sizes (data not shown). The higher soil temperature situations (>16^{o}C) are likely to be crops following oilseed rape, here increasing rainfall post sowing may be positively correlated with slug activity and increased variability in establishment

3.2.6 Soil type

From an initial analysis using individual soil types, soil texture accounted for 11.6% of the variation in autumn establishment (4.9% for spring establishment) (table 3.2). A wide range of soil texture categories were recorded, ranging from sand and loamy sand to silty clay and clay. Analysis of individual soil types was inconclusive because of variation in the amount of data from each type, results were therefore grouped and analysed in three categories, sands, loams and clays to help distinguish the major effects of soil type on establishment.

This analysis indicated that sandy soils had much better establishment than other soil types (figure 2.7). Sandy soils are friable over a much wider range of soil moistures. As such sandy soils are more likely to provide good seed soil contact increasing the speed of imbibition and germination. Lower soil strength associated with sandy soils also allows unrestricted root and shoot growth and reduces the chance of seedlings being impeded following germination, although some sands are at risk of capping as described in chapter

2.These lighter soils also tend to be free draining reducing the likelihood of water logging. Also, although sands tend to hold less water under dry conditions than heavier soils, they require only a tenth of the rainfall that a clay soil requires to reach the same critical soil water potential for germination (Annon, 1982). Thus over the wide range of sowing and post sowing conditions analysed in this study, sandy soils are more likely to provide good conditions for rapid germination and establishment.

The difference in establishment between loams and clays was much smaller than might have been anticipated. It might be expected that loams would have considerably better establishment due to their improved friability compared to clay soils. It is worth noting here that of the 692 records classified as loams, 78% were silty clay loams, weighting this group towards the heavier less easily cultivated soils, and reducing the likelihood of differences in establishment. Clay and clay loams can both create difficulties in seed bed preparation as they are friable over a very narrow range of soil water potentials, increasing the chances of poor seedbed preparation, poor seed soil contact and coleoptile impedance during emergence. When dry they must take up 30% of their volumetric water content before reaching the required soil water potential for germination (Annon, 1982), and when saturated they tend not to drain freely increasing the probability of waterlogging.

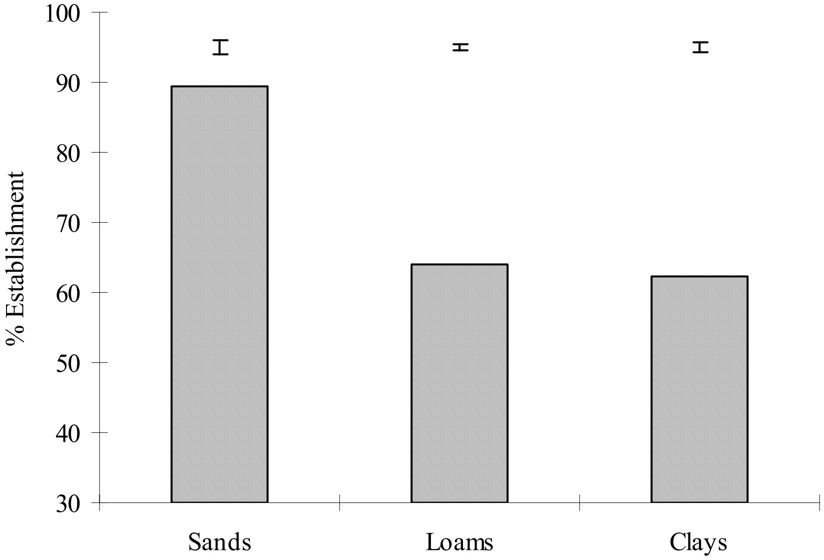

Figure 3.7 Soil type on autumn establishment, error bars indicate the SE of the mean.
For this analysis Sands include sand, loamy sand and sandy loam, Loams include sandy silt loams, silt loams, sandy clay loams and silty clay loams. And Clays include clay loams and clay soils. Error bars indicate the standard error of the mean.

An additional soil factor likely to be important is the stability of the soil. However this is infrequently recorded in experiments, and therefore could not be accounted for in this analysis. Unstable soils are at risk of slumping and capping, if there is a high rainfall post drilling, restricting crop emergence.

3.2.7 Previous cropping

Previous cropping is likely to affect levels of trash, slug activity, and autotoxicity as well as the amount of water available in the soil. The impact of previous cropping may also be confounded by indirect effects, for example late harvested crops such as potatoes and beans may delay subsequent sowing, and crop suitability to specific soil types may mean differences in establishment are not directly due to the previous crop.

The results showed that 79% establishment was achieved in wheat crops that followed Oats. Crops following set-aside, peas and potatoes had an average establishment of between 66 and 72%. Potatoes had the highest level of variation in establishment (Standard Error of the mean = 3.16). Where the previous crop was wheat or oilseed rape, average establishment was close to 62%, and after Beans average establishment was 54% (figure 3.8).

The high establishment achieved following Oats can in part be attributed to reasonably early sowing on light soils. The average sowing date where wheat followed Oats was 3 October, and sandy loams were the predominant soil type (75% of records).

Where the previous crop was peas, set-aside and potatoes, soil types were mainly silt and clay loams. Poorer establishment following potatoes can in part be explained by sowing date effects. Average sowing dates for crops sown after both peas and set-aside were the 17 & 18 Sept respectively, however, following potatoes the average sowing date was 19 November.

Poor establishment observed where wheat followed wheat may be partly due to both sowing date and soil type. As with crops following set-aside, peas and potatoes these crops were predominantly (70.3%) sown on the silts and clay based soils. Also the average sowing date for wheat after wheat was 13 Oct, later than peas and set-aside but earlier than potatoes. Sowing date differences may therefore explain the poorer performance compared to peas and set-aside. However, the poorer establishment where wheat followed wheat compared to where wheat followed potatoes, could not be fully explained by sowing date or soil type differences. Crops after potatoes were sown later, and so it might be expected that establishment would be poorer, however they are not statistically different and there was a tendency for the crops after potatoes to have better average establishment although much more variable. It is possible that the poor establishment when wheat follows wheat may in part be associated with autoxicity from previous crop residues (Alam 1990) or a build up of crop specific pests and diseases.

Where either beans or oilseed rape was the previous crop, the poor establishment compared to other crops could not be fully explained by soil type or sowing date differences. This is especially noticeable for wheat following oilseed rape, where earlier sowing compared with situations where previous cropping was wheat or potatoes, on similar soil types, did not result in better establishment. Wheat following beans also showed particularly poor establishment, although this may be more influenced by the late sowing (19 Oct). However slug levels may be a significant explanatory factor, as they are known to be higher in crops following oilseed rape and beans (Glen 1989).

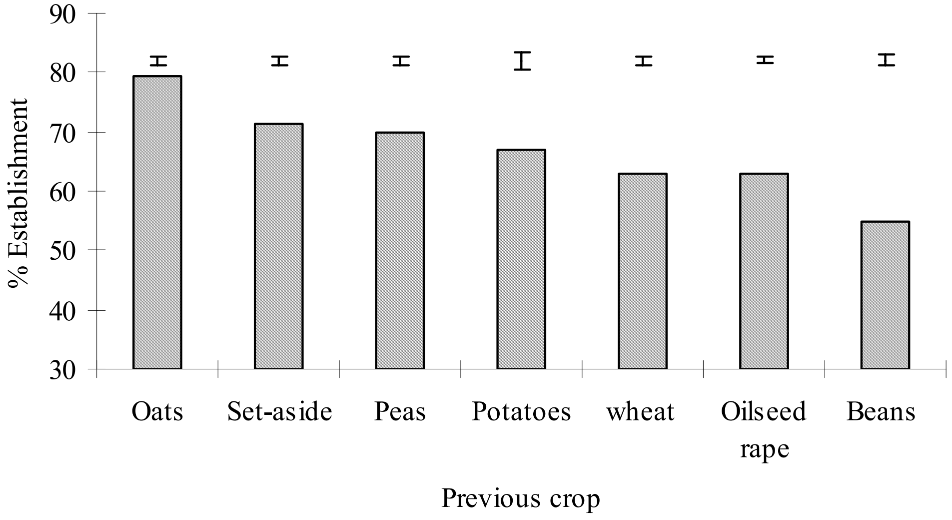

Figure 3.8 The effect of previous cropping on establishment. Error bars indicate the standard error of the mean.

3.2.8 Cultivations

3.2.8.1 Primary cultivations

The ease with which water moves into the seed is determined largely by the seed soil contact, which in turn is affected by the soil aggregate size distribution of the seedbed Bouaziz and Bruckler (1989a). Primary and subsequent cultivations determine the seedbed structure and the level of seed soil contact. The efficacy of any cultivation treatment, and the need for subsequent treatments will, however, depend on a number of factors, such as the soil type, and soil moisture, which affects the friability of soils. A single pass with a cultivator after ploughing may be sufficient on a sandy soil under many circumstances. On soils that exhibit stronger cohesive forces such as clays, soil moisture will affect friability. Friability is therefore likely to vary considerably with site and season meaning that the number and type of cultivation treatments does not correlate with the quality of the seedbed. Few of the experiments in the data review specifically investigated the effects of seedbed quality on establishment, so in most cases, growers would have been aiming to create a seedbed suitable for wheat. Within this data set ploughing was by far the most prominent form of primary tillage accounting for 93% of records where autumn counts were conducted. Nearly all cases where ploughing was not used the soils were clays and silty clay loams. As such to limit the influence of soil type the analysis looked specifically at the establishment achieved following ploughing and non-ploughing forms of primary cultivation on these soil types. The result indicated that despite the mean establishment appearing to be slightly higher where ploughing was used, there was no statistically significant difference in establishment between ploughing and non-ploughing forms of primary tillage (figure 3.9).

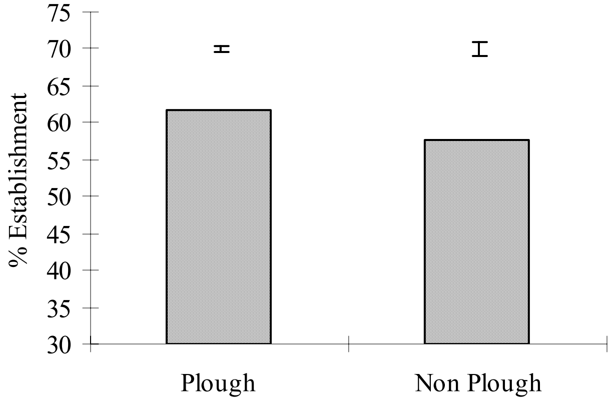

Figure 3.9 The effects of different primary cultivations strategies on autumn establishment on silty clay loam and clay soils.

It might have been expected on these soil types that shallower non inversion strategies might help preserve any surface tilth formed as a result of self structuring and hence might result in good seedbed conditions, better seed soil contact and faster germination. It is possible any such positive effects may be balanced by the benefits of ploughing down trash that could impair germination, and possibly the negative effects of shallower non inversion establishment that can limit water infiltration causing water logging.

3.2.8.2 Secondary cultivations

To investigate the effects of secondary cultivations on establishment, a comparison was made of the levels of autumn establishment where power harrowing, discing or tines were used as the secondary tillage. Mean establishment following power harrowing was 66.0%, where discing this was not significant different (P>0.05) although showed a trend to be lower at 62.1% and where tines were used 79.8% establishment was achieved, whichws significantly higher than both the other two treatments (P<0.001) (figure 3.10).

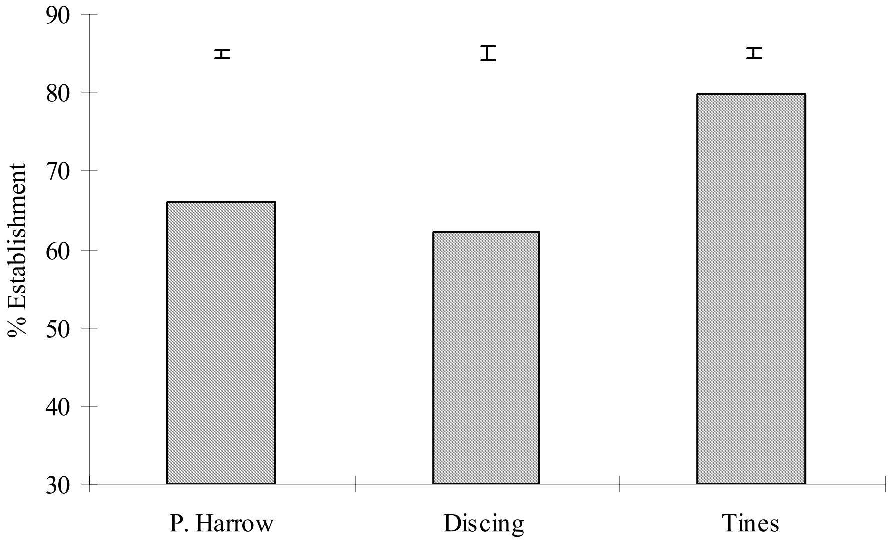

Figure 3.10 The effect of secondary tillage choice on establishment, error bars indicate the standard error of the mean.

The method of secondary cultivation investigated here does not necessarily relate to eventual seedbed tilth, as in many cases subsequent cultivations took place. The results observed here may relate to the potentially negative effects of discing and power harrowing in terms of soil structure on heavy land. Discing in inappropriate situations may cause over consolidation below the surface tilth layer resulting in poor water infiltration and leaving seedbeds that are more prone to water logging. Over-cultivation with a power harrow, may also reduce water infiltration and increase capping.

3.2.8.3 Effects of rolling on establishment

Cambridge rolling, or consolidation of the seedbed under dry conditions is widely practised to improve seed soil contact and hasten imbibition, germination and establishment. Using the autumn establishment information, a comparison was therefore made of the 319 cases where seedbeds where rolled and the 572 that were not. The results indicate that where rolling was practiced establishment was significantly better than where it was not (figure 3.11). However this may be reflected in soil type differences between the two categories. Of the soils that were rolled, 28% were sands (as previously classified), whereas on unrolled seedbeds this was just 3%.

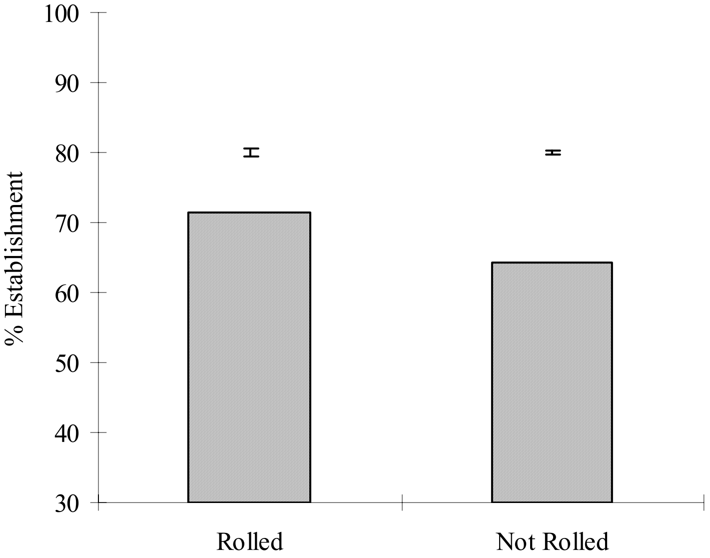

Figure 3.11 The effect of consolidation by Cambridge rolling on establishment.

Anecdotal evidence suggests that whereas under dry conditions rolling may improve seed soil contact and hasten germination, rolling may have deleterious effects on establishment leading to over consolidation of the seedbed. Further analysis was used to establish if there was and interaction between consolidation and pre- or post-sowing rainfall. No significant interaction was observed. The highest percentage variance accounted for was 7.1 with 5 days post sowing rainfall.

The lack of any effect most probably relates to the cultivation strategy employed. In any given situation the grower will have sought to achieve good establishment by rolling where seedbeds are dry, and not rolling when moisture is abundant. No experiments in the data directly compared the effects of rolling against not rolling on establishment.

3.2.8.4 Cultivations summary

For the majority of experiments in this analysis, in each situation the cultivations strategy should have reflected best practice at the time for the given conditions, aiming to create conditions that would lead to a rapid emergence and an evenly established crop. As such it may be that differences in establishment as a result of cultivation observed in this analysis may actually reflect the different cultivations practices employed at different locations, differences in sites, soil types and previous cropping that might have led to a particular strategy being employed. The number of experiments that specifically looked at the effects of cultivations on establishment was insufficient for a more in depth analysis.

3.2.9 Variety

The data set contains a total of 59 different varieties. For the purposes of comparison this was narrowed down to seven which featured over 50 times in the data. Establishment ranged from 61% for cv. Spark, up to 73% for cv. Claire (figure 3.12).

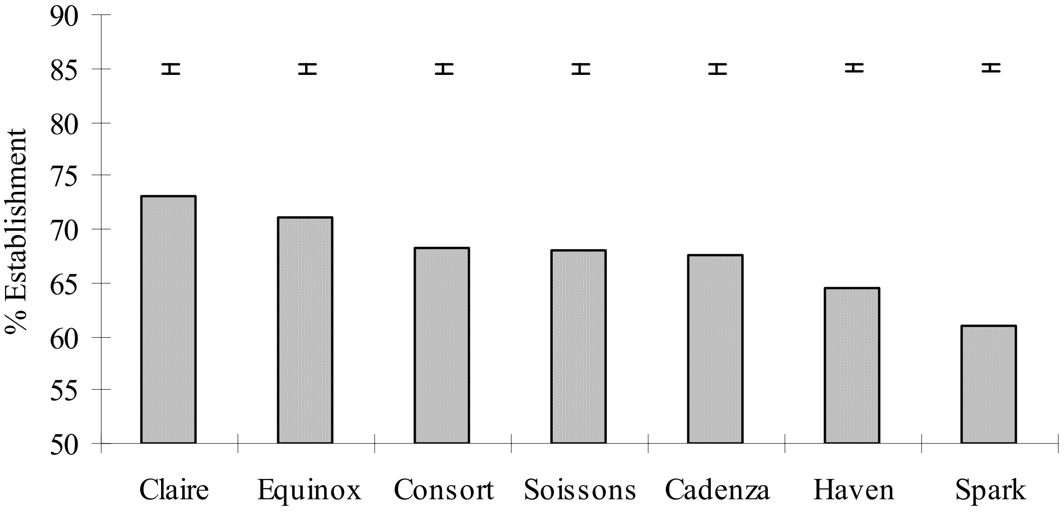

Figure 3.12 The effect of variety on establishment Error bars indicate SE of the mean.

These differences in varietal establishment might be expected to be linked to a number of factors such as their selection for their suitability to specific sowing dates, soil types and seed size. Although these factors may have an influence, they do not fully account for the differences observed. The mean sowing date for Spark was 19 October, whereas for Claire it was the 23 September, however both Haven and Soissons the mean sowing date was the 20 October. No major soil type differences existed between Spark, Haven and Soissons, with 21-24% of crops being sown on sand soils, 58-76% on Loams and 1-21%

being sown on clay soils. The varietal differences may relate to differences in thousand grain weight a factor known to affect establishment(Naylor, 1993), this may also explain the low establishment in Spark, as in the 1999 NIAB recommended list it has a thousand grain weight of 37.7g, whereas all other varieties ranged between 40.9 and 49.6g (NIAB, 1999). Seedling vigour has also been linked to plant breeding and genetics (Wibberley 1989) which may affect the later stages of establishment, it has also been suggested that cultivars may differ in their partitioning of resources to the roots and shoots and that under low soil water potential conditions fast-rooting lines showed improved emergence (Gul and Allan 1976). Successful emergence from depth has been linked to elongation of the subcrown internode, a reaction known to be affected by variety (Poulos and Allan, 1987), however this would only explain the variety differences if the crops used in this analysis were consistently drilled too deep.

3.2.10 Regional effects

The location of any given experiment accounted for 24.9% of the variation in autumn establishment. Only sowing date accounted for a larger proportion (table 3.2). Differences in establishment by site may relate to a number of factors including soil type, and cultivations strategies, as already mentioned. To assess the impact of geographical location on establishment sites were grouped into three categories to represent Scotland and north east England, the east midlands and south east, and the west midlands and south west (figure 3.13)(appendix B). The east and south east of England showed the highest level of autumn establishment at 78.3%, compared to Scotland and the North East at 69.5% and the West and South West at 60.1%. The overall levels of spring establishment using all records where spring establishment was recorded, suggests that the highest percentage of over winterkill appears to be in the East and south east, although spring establishment levels were still at a similar level to other sites. As might be expected Scotland and the North East showed a tendency to have poor spring plant populations than the other areas of the country, and the west and south west tended to have the lowest level of over winter kill.

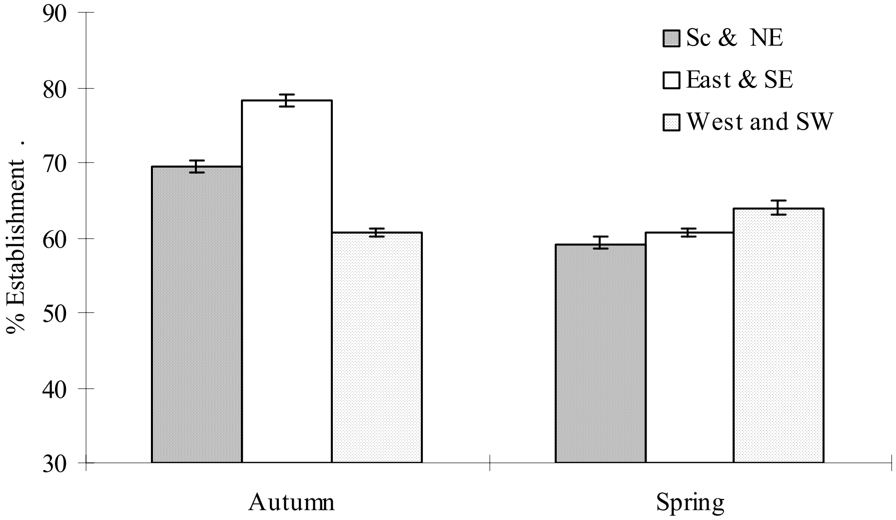

Figure 3.13 The difference in autumn and spring establishment between region*s,* error bars indicate the SE of the mean.

The regional effect observed in autumn establishment may well relate to the balance of soil types between the regions in this analysis. In Scotland and the North East, 9.8% of the soils were sands or sandy loams, in the East and South East this was 31.3% whilst in the West and South west where establishment was the poorest, only 3.8% of the soils were sands. This poor establishment in the west may also relate to higher autumn rainfall and increased chances of autumn waterlogging affecting establishment and early winter plant survival, as well as generally warmer temperatures encouraging slug activity. The spring establishment counts show no significant differences between the regions, however a comparison with the autumn counts does suggest that, although autumn establishment is poorer in the west and south west, this region may suffer less from winter kill than the east and north.

3.2.11 Seed rates

Poorer establishment, reported at higher seed rates is believed to be associated with allelopathy effects as discussed in the literature review. In order to test the consistency and magnitude of this effect, a parallel line regression analysis on all 44 of the seed rate trials was conducted. This showed that on average the percentage establishment is reduced by 2.6% for every 100 seeds m^{-2} increase in seed rate (Figure 3.14). This is an actual change in % establishment rather than a % change, so for a field that would achieve 60% establishment at 400 seeds/m^2, we could expect 67.8% establishment at 100 seeds/m^2

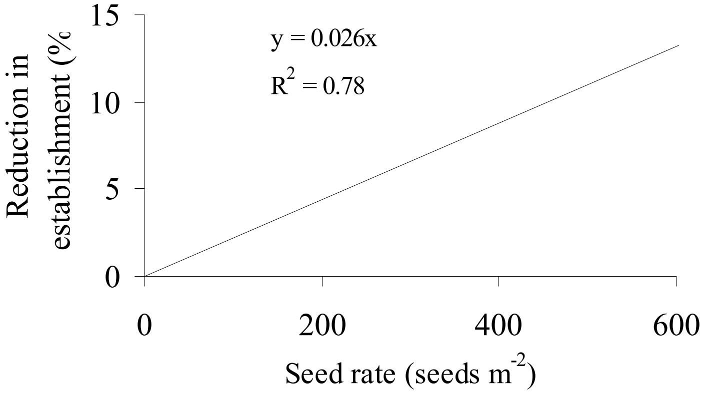

Figure 3.14 The effect of seed rate on establishment.

This gradient represents the average effect on establishment, This change in establishment was not consistent amongst all of the trials however is some experiments the gradient was as high as 0.15, constituting a 15% reduction in establishment for every 100 seeds m^{-2} increase, whilst in other experiments there was no effect at all.

The allelopathic effects described above are likely to contribute to the relationship for reduced establishment with later sowing.

3.3 Summary

- Sowing date had the greatest effect on establishment, with establishment decreasing from about 70% for September to early October sowings to 60% in late October, to less than 50% in November and later.
- The effect of sowing date appeared to be caused by lower soil temperatures, with establishment decreasing rapidly when the soil temperature at 10cm depth fell below 8^{o}C.
- The effect of rainfall was complex, with post drilling rainfall improving establishment when the soil temperature was above 12^{o}C, but decreasing establishment when it was below 12 ^{o}C.
- Sandy soils had 90% establishment compared with 65% for loams and clays.
- The E Midlands and SE had 78% autumn establishment, NE and Scotland (69%) and S and SW (60%). These effects probably reflect the proportion of sandy soils in each region.
- Cultivation type appeared to have little effect on establishment, although there were insufficient types of cultivations within the survey to allow strong conclusions to be drawn.
- Establishment after oats was 79%; Potatoes, set-aside and peas was 66-72%; wheat, rape and beans was 54-60%.
- Variety choice had relatively small effects, but could affect establishment by 10%.

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APPENDIX A

Grouping of sites for regional analysis

Scotland & North East England

Path Head, Edinburgh
Cockle Park, Newcastle
Edinburgh
Aberdeen
RNAS site, Aberdeen
ADAS High Mowthorpe, North Yorkshire
Bainton, North Yorkshire

East Midlands +South East England

ADAS Gleadthorpe, Nottinghamshire
Sutton Bonington, Liecestershire
Ropsley, Linconlnshire
ADAS Boxworth, Cambs
ADAS Arthur Rickwood, Cambs
Kettering
Biggleswade
Shottenden, Kent
Braeburn, Kent

South West + West Midlands

Drayton, Warwickshire
Cirencester
Harper Adams University College,
ADAS Rosemaund, Herefordshire
Lower Hope Farms, Herefordshire
ADAS Mamhead, Devon
ADAS Bridgets, Hampshire
Manydown, Hampshire