HGCA

PROJECT REPORT No. 169

RESEARCH TO UNDERSTAND, PREDICT AND CONTROL FACTORS AFFECTING LODGING IN WHEAT

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by

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ABSTRACT

The aim of this study was to lessen lodging in winter wheat by providing a guide to how factors affect lodging and by testing whether spring crop assessments could identify lodging-prone crops.

An aerial survey of 340 fields (2865 ha) in 1991-92, quantified the extent of lodging in a widespread lodging year. 91% of fields had some lodging, resulting in 16% area lodged. From these values it was estimated that a severe lodging year costs the UK wheat industry £60 million through yield loss and a further £60 million due to loss of bread making premium, grain drying costs and delayed harvest. 95% of lodged fields had lodging within the overlaps between the field margin and field centre, but only 2% had lodging immediately adjacent to the field tramlines. Regional differences in lodging were closely linked with soil type, rather than rainfall and wind speed, with most lodging on silt soils. The percent area lodged per field commonly varied from 10 - 90% within individual localities.

A model of the lodging process accounting for weather, soil and crop factors was developed to investigate which factors influence lodging most. Simulations for a wide range of crops and environments expected in the UK predicted root lodging to occur more frequently than stem lodging. Variation in clay content and macroporosity of the soil influenced lodging more than rainfall and wind speed. Importantly, variation in the structure of wheat crops influenced the risk of stem and root lodging as much as variation in soil type and weather. The plant characters which influenced lodging most included shoot height at centre of gravity, natural frequency of shoot oscillation and the number of shoots per plant, which affect shoot and plant leverage; stem diameter and material strength of the stem wall, which affect stem strength; and the spread of the root plate and depth of structural roots, which affect anchorage strength.

A field experiment was used to develop the lodging model and to investigate possible spring predictors of lodging. Two levels for each of sowing date, seed rate and soil residual N were factorially combined. Within each treatment four levels of lodging control, untreated 5C cycocel, 5C cycocel with Terpal and Canopy Management were compared. 13% of the 1993-94 experimental plots root lodged, 33% plots stem lodged in 1994-95 and 82% plots root lodged in 1995-96. Large treatment differences were found for the percent area lodged and in the values of the lodging-associated plant characters. Early sowing produced shoots with a high centre of gravity and slow natural frequency, resulting in greater shoot leverage and increased risk to stem and root lodging. Fertile soils in combination with early sowing reduced stem diameter and material strength of the stem wall, which resulted in weak stems and greater stem lodging risk. High seed rates reduced root plate spread resulting in poor anchorage and greater root lodging risk. Plant growth regulators reduced height at centre of gravity and increased natural frequency, reducing shoot leverage by up to 30%, but had no effect on the strength of the stem base or anchorage system. Reduced N applications with Canopy Management reduced shoot number per plant which decreased plant leverage. This also improved stem strength on fertile

soils. Preliminary investigations showed large genotypic variation in all the lodging-associated plant characters.

Spring crop assessments were proven to be indicative of later developing lodging-associated plant characters and thus lodging risk. Root plate spread and structural rooting depth at grain fill were negatively correlated with spring plant density. Crops with 150 plants m^{-2} had four times the anchorage strength of crops with 500 plants m^{-2}. Stem diameter and wall width at grain fill could be predicted from spring canopy size and shoot number m^{-2}. Crops which were lush in the spring, with canopy green area index (GAI) 3 and 1500 shoots m^{-2}, resulted in narrow thin walled stems which were approximately half as strong as stems in sparse crops with GAI 1 and 500 shoots m^{-2}. Shoot number per plant and plant leverage force were negatively related with spring plant number m^{-2}. Theoretical prediction schemes were developed for shoot height at centre of gravity and natural frequency based on additional spring measurements of soil N supply, final leaf number per main stem and rate of leaf emergence (phyllochron).

This study has shown that taking the correct decisions at sowing can reduce lodging risk without adversely affecting yield potential. Methods of reducing lodging risk include avoiding early sowing which results in tall crops with high leverage, reducing seed rate to strengthen crop anchorage and avoiding excess N supply before stem extension to prevent the production of weak stemmed crops. The importance of structurally strong topsoil to improve crop anchorage is also identified. Furthermore, methods by which growers can assess lodging risk in the spring are given which will help lodging controls to be targeted at the crops with greatest lodging risk. In spring, large canopies with many shoots indicate crops with potentially weak stems which will be prone to stem lodging, and large plant populations with poor structural root development indicate poorly anchored crops which will be prone to root lodging.

Thus the aims of this study have been achieved by identifying the main factors which promote lodging and showing that their values during the grain fill period can be predicted from assessments of the spring crop. Some of this work is applicable now, but further work is required to test the lodging model, further develop and test the lodging predictions, identify the lodging-associated plant characters as varietal traits and to investigate the effectiveness of more lodging control methods.

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GENERAL ABBREVIATIONS

kg = kilograms

g = grams

t = tonnes

l = litres

ha = hectares

Hz = hertz

Nm = newton metre

Nmm = newton millimetre

mm = millimetre

cm = centimetre

m = metre

s = second

GAI = green area index

N = nitrogen

DM = dry matter

OM = organic matter

GS = plant growth stage (Zadok's)

PGR = plant growth regulator

HI = harvest index

TGW = thousand grain weight

SPWT = specific weight

cv. = cultivar

LTM = long term mean

ADAS = Agricultural Development and Advisory Service

MAFF = Ministry of Agriculture, Fisheries and Food

NIAB = National Institute of Agricultural Botany

OBJECTIVES

To lessen lodging by defining those crops for which some change in management is likely to be cost effective by :

- **providing in this final report, a guide to factors influencing lodging risk, how their influences relate, how these are best countered, and what the costs and benefits may be.**

- **testing whether crop inspections in spring, together with wider crop intelligence, can significantly improve the assessment of lodging risk.**

1. INTRODUCTION

Whilst wheat sways in the wind, all seems well. But a collapsed crop, lying flat in the rain spells a poor and troubled harvest. To an extent these so called 'laid' or 'lodged' crops are thought to be a problem of the past. Varieties of wheat grown since the late 1970s have improved 'standing power' (as rated by the National Institute of Agricultural Botany in their recommendations). However, lodging still occurs, and its occurrence is far from random. Patterns of lodging provide clues to its causes and promises of more comprehensive control. This report seeks to assess these patterns, paying particular attention to the widespread lodging season of 1992, and to experimental evidence of the way husbandry can change the form of the crop. Then, taking into account the findings of previous research, the report seeks to forge a comprehensive explanation of lodging on which might be based more precise techniques whereby UK wheat growers could further restrict its occurrence.

In terms of the structure of the plant, lodging is a catastrophe. Lodging is an irreversible collapse of the plant's structure. This is commonly believed to result from buckling of the stem base (stem lodging), although anchorage failure (root lodging) is also known to be a cause. The mechanisms of lodging are discussed further in Chapter 3. Lodging can be considered as an event occurring within one day, and although lodged stems may initially lean rather than lie completely horizontal, for the most part each patch of crop can be classed as either lodged or unlodged.

On a spatial scale, there are evident patterns of lodging :

- within fields, for instance as shown by the 'tramline effect',
- between fields for instance associated with different varieties, husbandry or soil,
- between farms probably through different farming systems, and
- between regions within the UK contrasting in particular the north and west with the south and east.

Similarly, through time, lodging is seen to be associated with particular weather events, particular parts of the year, and particular seasons.

The influence of crop husbandry is seen primarily to affect field to field variation in lodging. This will be considered later in the report. However, other components of variation in lodging are important in providing a context for a consideration of its control.

Within a field, the headlands tend to be the first part to show lodging. Drill, spreader and sprayer bouts tend to overlap on headlands so these patches are likely to relate to the effects of seed rate, nitrogen fertiliser and agro-chemical application that will be discussed later. Some fields have areas such as valley bottoms where lodging is a perennial problem. Often these are thought to be particularly fertile causing lush and tall growth, or particularly wet causing poor root anchorage, or they may be particularly exposed in high winds. The 'tramline effect', where fields with widespread lodging commonly show upright plants beside wheel-ways continues to be a conundrum. Many different opinions are expressed as to the cause of this, including greater soil compaction along tramlines (leading to better anchorage), reduced competition for water, light and nutrients (leading to stronger plants) and differences in wind gusting and micro-climate down the tramlines. These have been the subjects of debate in the farming press (Crops Magazine 14.8.85 & 28.8.85; Arable Farming, September 1985).

There are observed differences in the occurrence of lodging between fields which may be associated with the field's history. Perhaps it used to be meadow-land and the soil has a high organic matter content, promoting lush growth. The field may have regularly received applications of slurry or farm-yard manures. Alternatively there may be shallow soil or factors which inhibit good root anchorage or promote stem diseases.

Differences between farms have been less easy to quantify, but there is anecdotal evidence that, in seasons of widespread lodging, particular farms have been identified with markedly more or less lodging than the norm. Perhaps the farm policy has been to be particularly generous or frugal with N fertiliser applications, or the farm system generates large quantities of animal manures, or the farmer is particularly skilled in the choice of varieties or the application of growth regulators. Any evidence of farm to farm variation supports the aim of further constraining lodging risks.

Lodging is recognised as a particular problem in Northern Ireland, Wales, northern Britain, and the west country. Clearly these are regions with wetter summers but they are also more exposed in windy weather systems, they are cooler so that their wheat crops develop more slowly and are harvested later, their farming systems involve more livestock and their soils, even without livestock, tend to contain considerably more organic matter. The organic soils of the Fens and other peaty soils also have a reputation for prevalent lodging.

Within any season the crop appears to be most vulnerable to lodging as harvest approaches. On occasions snow or very severe weather after the start of stem extension has caused early lodging but this is rare. Lodging normally occurs after ear emergence and particularly during grain filling and ripening.

The most significant aspect of the temporal variation in lodging is the contrast between seasons. Since varieties with good standing power were introduced in the late 1970s widespread lodging has occurred in 1980, 1985, 1987, 1992 and 1997. These were all years with wet summer weather. However, it is apparent that not all years with wet summers have been years with widespread lodging. Thus there is scope to analyse the weather patterns over all the past 20 years to identify more closely the conditions that lead to this type of 'catastrophic' lodging.

Through observation of these patterns there has emerged a consensus that lodging occurs where and when tall, weak strawed plants are subjected to wet and windy weather. However, much is still left unexplained. The 'tramline effect', observed differences between different soil types and farms, and contrasts in lodging between apparently similar weather conditions cannot be accounted for by this coarse summary. There is a need to devise a more precise description of the structure of a wheat crop, the way it is anchored and how it is affected by the weather if we are to reconcile all aspects of the experience of lodging that has accumulated in the industry. In this study, we aim to devise such a description. The acid test of this will be to see the extent to which we can account for the common observations using knowledge of crop structure and function. If successful we can then suggest whether growers have any misconceptions about lodging.

Before attempting an explanation of lodging and suggesting ways of improving husbandry, we must first consider the costs of lodging to the industry, and summarise the way that husbandry decisions are currently seen to affect this.

1.1 THE COSTS AND PENALTIES OF LODGING

When extensive lodging occurs, costs to the industry are large, through poor grain quality, the need for greater drying, lower yields, delayed harvest, and grain losses at harvest (Table 1.1). Experimental evidence from ADAS Rosemaund where the effect of lodging on grain yield has been investigated showed that lodging associated yield penalties were in the range 0.5 to 4 t ha^{-1}. The severity of yield loss was dependent on the growth stage at which lodging occurred, with on average 2.5 t ha^{-1} being lost due to lodging. It appears that widespread lodging has occurred one year in four through the past two decades and, if we take 1992 as representative (Chapter 2), we can assume that on average 16% of the 1992 wheat crop was estimated to have lodged on each occasion. The lost yield in 'lodging years' may therefore be of the order of 0.7 million tonnes and cost £60 million. In other years lodging in the wetter regions, on certain farms, groups of fields, or within fields may amount to 0.5-1% of the crop. Thus the average annual direct cost in lost yield in a non-lodging year probably amounts to £0.1 million.

The costs through delayed harvesting, slower harvesting, lost grain quality and increased drying are less easy to quantify. It is important to recognise that, except for slower harvesting for which the cost is sufficiently small to ignore, these must relate to a considerably larger area than just the area that shows lodging, because fields and their produce normally must be harvested and processed as one. About half of the fields surveyed in 1992 (Chapter 2) had more than 10% of their area lodged. So, assuming that half the crop in 'lodging years' is harvested a week late, resulting in a small yield loss of about 0.1 t ha^{-1} (estimated from growth analysis of the variety Mercia under HGCA Project 0044/1/91 in 1993 and 1994), that the grain from these fields has an additional 3% of its fresh weight which must be removed by drying costing about £4 per tonne, and that, of the quarter of this wheat that was intended for milling, half (i.e. 0.75 million tonnes) incurs a loss of premium of £20 per tonne, these additional costs amount to over £60 million in a 'lodging year'. It is assumed that the proportion of the crop affected in this way in a non-lodging year would be insignificant.

Table 1.1 An estimated <u>average annual</u> cost of lodging to the UK wheat industry.

Average costs per year:	*Total £/ha*	*UK total £million*
Average yield loss due to lodged patches	8.0	13.6
Average yield loss due to delayed harvest	0.7	1.2
Extra drying cost of lodged crops	3.7	6.2
Loss of quality premia	4.7	8.0
PGRs	6.2	10.6
TOTAL	**23.3**	**39.6**
Assumptions :		*units*
Area of wheat per year	1.7	*ha*
Average yield of wheat	7.5	*t/ ha*
Proportion of wheat for breadmaking etc.	0.25	
Value of grain	80	*£/t*
Average quality premium	20	*£/t*
Proportion of area lodged in a lodging year	0.16	
Proportion of fields affected in a lodging year	0.95	
Proportion of fields with >10% lodging	0.50	
Frequency of lodging years	0.25	
Yield loss due to lodging	2.5	*t /ha*
Delay in harvest due to lodging	7	*days*
Yield loss due to delayed harvest	0.01	*t/ha/d*
Greater moisture content of lodged crops	3.0	*%*
Cost of drying grain	1.3	*£/t/%*

In addition, a total of £10.6 million is spent annually on plant growth regulators (PGRs) for winter wheat, irrespective of whether lodging occurs in that year (Garthwaite *et al.*, 1996). Thus the total cost of lodging in winter wheat amounts to some £130 million in a 'lodging year' and about £40 million per year on average. On average, the cost of lodging to the individual grower is £23 ha^{-1} (Table 1.1), which equates to £75 ha^{-1} in a lodging year. It must also be noted that the lodging survey described in Chapter 2 found some sites to experience 25 –30 % area lodged. At such sites the cost to the grower would be over £140 ha^{-1}.

These are the costs of lodging to the UK wheat growing industry that the research reported here, and that undertaken in future, must seek to reduce by enabling farmers and agronomists to predict more precisely where and when lodging is likely to occur so that expenditure on lodging control can be more accurately targeted and lodging itself reduced.

1.2 HOW HUSBANDRY AFFECTS LODGING

There is a wealth of experience of lodging control measures which have lead agronomists and farmers to believe husbandry decisions to be of major importance in affecting lodging.

1.2.1 Variety

Significant improvements in the standing power of commercial wheats were made in the late 1970s with the introduction of semi-dwarf varieties which were shorter than previous introductions. Currently both standing power and shortness of straw are scored in the list of varieties recommended for the UK on a 1-9 scale (Table 1.2). On this list, the tallest varieties tend to have poor standing power, but shortness does not guarantee good standing power; of the shortest varieties Buster has a standing power of 9 whilst Charger is only scored 5.

Table 1.2. The relationship between shortness and standing power for currently recommended varieties of winter wheat (NIAB, 1998).

Shortness of straw	*Variety*	*Standing power*
9	Equinox	9
8	Buster	9
	Caxton	6
	Charger	5
	Abbot	7
	Consort	8
	Brigadier	7
	Madrigal	7
	Harrier	6
7	Riband	8
	Hereward	8
	Reaper	6
	Beaufort	8
	Soissons	7
	Savannah	8
	Hussar	6
6	Rialto	6
5	Spark	7
4	Cadenza	6

1.2.2 Sowing

Early sowing increases stem length in wheat (Fielder, 1988) which increases lodging risk. Seed rate affects the final plant population and can alter a crops lodging risk (Easson *et al.*, 1993), but it is not clear whether this is because of differences in competition between plants and hence height, altered tillering, effects on root formation or a combination of these. Furthermore, a high plant population density is more likely to lead to lodging, as plants crowded together are more prone to stem base disease (especially eyespot) which weaken the stem.

There are conflicting views on the effect of sowing depth on lodging. Some advocate shallow drilling as a lodging control measure and others deep drilling. The seed dressing Baytan has a growth regulatory effect on plants by reducing the potential extension of the sub-crown internode (Montfort *et al.*, 1996). This will cause deeper crown formation which may enhance anchorage.

Soil type cannot be changed and may to an extent be the overriding factor in many cases. However, soil and seedbed structure can be influenced by cultivations and farmers may roll in the autumn and/or spring to help prevent lodging.

1.2.3 Nitrogen

Over fertilising is a common cause of lodging as plants elongate faster, producing tall, lush crops with weaker stems. So the positive effects of nitrogen in terms of yield potential (such as larger leaves, more tillers, longer roots and more dry weight gain) have adverse repercussions in terms of lodging proneness (directly or due to disease).

1.2.4 Disease

The most important lodging related disease is eyespot. Varieties vary in their resistance to eyespot and no fungicide will give total control of the disease at present. Eyespot infections can be severe and in 1987 eyespot was the most serious disease in winter wheat, causing average yield losses of 0.58 t ha^{-1} nationally, which cost the industry £29 million. Severe eyespot greatly increases lodging risk and this may have been a significant factor in causing lodging in 1987.

Other diseases such as fusarium and take-all are also likely to increase lodging risk. Fusarium weakens the stem base and take-all infections weaken or destroy the root system which reduces anchorage thus increasing lodging risk. However, take-all is also associated with light ears, which may counteract the increased lodging risk through loss of anchorage.

1.2.5 Plant growth regulation

PGR application modifies plant development processes including, reducing the length of the lower internodes and delaying the start of stem extension. Some PGR manufacturers also claim stem strengthening and improved rooting properties for a few products. In wheat, chlormequat (e.g. Cycocel) applied between GS 30 and GS 31 to reduce extension of the lower internodes, is the most commonly used chemical for preventing lodging. Ethepon products may also be used (e.g. Terpal) to give control of lodging between GS 32-45, in order to reduce upper internode extension.

Lodging control is the most significant role for PGRs in order to help delay the onset or reduce the degree of lodging. The decision to use PGRs can be vital as lodging can reduce yield by as much as 4 t ha^{-1}.

1.3 FURTHER SCOPE TO CONSTRAIN LODGING

1.3.1 Improvements in husbandry

Current guidelines for lodging risk are very general and tend to be qualitative rather than quantitative, e.g. NIAB varietal standing powers (Table 1.2) and the ADAS plant growth regulator use scheme (Appendix 1). Apart from guidelines such as these, lodging control is often based around local practice and farmers intuition, which vary widely.

The development of an effective prediction system for lodging risk in wheat would be of great benefit to the cereal industry. Individual crops at risk of lodging could be identified early in the growing season and the degree of risk quantified. Then measures should be devised to meet each source of risk. For example, if root failure is the predicted cause of lodging then the best option may be to roll the crop or encourage stronger, more prolific rooting. If stem failure is expected then a plant growth regulator can be applied or nitrogen fertiliser timing and rate could be altered to more accurately match the crops requirement and reduce lodging risk. Conversely crops at little or no risk of lodging could be identified and expenditure on plant growth regulators or other control measures avoided.

We can tell something of each lodging-related character in spring. We aim to look for loose tilth, or weakly binding soil, few or weak roots, thin, weak or weakened stems, and the potential for dense, wind and rain trapping canopies and heavy heads. Our understanding of how these characters combine could be used to calculate the risk that a crop will lodge, to suggest whether lodging is more likely through failure of the root or stem, and thus to pin-point the most appropriate controls.

Although lodging can be controlled, especially with PGRs, there may be some scope for re-assessing crop strategy for a following season; better standing varieties, less seed, tighter seed-bed structure, altered drilling depth, delayed establishment, and assessment of N residues, may severally or together counter the risks perceived without compromising yield, and thus improve farm strategy.

1.3.2 Progress through breeding

In recent years, improved understanding of the growth and development of cereals has aided the breeding of better varieties and improved the definition of the wheat ideotype for modern agricultural conditions. Modern varieties tend to have shorter, stiffer stems with more erect canopies which are more efficient in light-use. Reduced stem growth permits better ear growth, resulting ultimately in increased yield and a higher harvest index.

However, there is no particular specificity in the attributes that breeders seek to improve with regard to lodging risk. It may be that breeders could improve 'standing power' more efficiently by identifying particular strengths and weaknesses of parent material in root growth, tillering habit, or strength of basal internodes, and by seeking the improvement which is most appropriate.

1.3.3 Crop Assessment

The research reported here is an integral component of an overall intention to refine husbandry of wheat according to assessments of crop progress. It is held that these assessments are just as relevant to the husbandman as to the plant breeder. However, assessment techniques are currently crude and qualitative. More accurate and precise assessments must arise from a combination of observations in the field and an understanding of the main underlying crop processes[1]. In this project, as in parallel studies, development of the understanding and of the techniques for crop assessment has been effected through both 'desk studies' and field experimentation.

In this final report we aim to provide a guide to factors influencing lodging risk, how their influences relate, how these are best countered, and what the costs and benefits may be. The desk studies have therefore aimed to provide a framework of understanding for the lodging process, to verify this against recent experience of lodging across seasons and sites, and against known agronomic affects.

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Thus (as outlined to the R&D Committee on 14 July 1992) this proposal complements H-GCA Contract 0044/1/91A 'Predictive information on plant development in relation to eventual yield and quality'.

2. A 'LODGING YEAR' : 1992

2.1 BACKGROUND

Of the last twenty years, 1980, 1985 1987, 1992 and 1997 have shown extensive lodging of wheat in the UK. Lodging in other years appeared much less common. However, the actual extent of lodging in one of these 'lodging years' has not been assessed. The aim of this chapter is to use aerial photographs taken soon before harvest in 1992 to assess the extent of lodging over a wide geographical area on an individual field basis. It was intended that risks of lodging and some factors affecting this risk, should be identified and quantified from these data, together with meteorological data, soil information and details of farming practices.

2.2 APPROACH

2.2.1 Origin of Data

Aerial photographs were taken by the ADAS Aerial Photography Unit (APU) between the 20th and 28th July 1992. The sites surveyed were ADAS Terrington (West Norfolk), ADAS Gleadthorpe (North Nottinghamshire), ADAS Boxworth (Cambridgeshire), ADAS Arthur Rickwood (Cambridgeshire), Kirton (South Lincolnshire), ADAS Bridgets (Hampshire), ADAS Rosemaund (Herefordshire), South Petherton (Somerset) and Odiham (Hampshire). The location of these sites is shown in Figure 2.1.

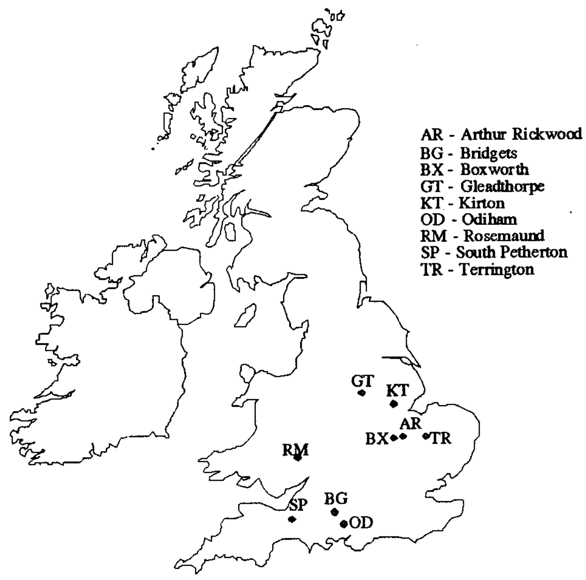


Figure 2.1 Sites for Aerial photography survey

All wheat fields belonging to the target farm were photographed. This involved taking a set of overlapping photographs over the farm and its surrounding area, to ensure that all the relevant wheat fields were included. Thus wheat fields outside the farm of study were also photographed and this provided an extension of the survey. Thus a 'general dataset' was produced which included all the wheat fields photographed, and there was also a 'detailed subset' of data on which more detailed information was available, comprising the wheat fields belonging to target farms. These more detailed data included information relating to the soil types and husbandry of each field.

2.2.1.1 General dataset

Data recorded

Data recorded in the general dataset were interpolated from the aerial photographs and site records. These included the site name, field shape, field size, percent area lodged per field, presence or absence of lodging in the margin or tramlines, presence or absence of a field trial or split field, soil series, soil type, part of field where lodging occurred as a compass bearing and whether the drainage was good or bad. Individual fields were defined by field boundaries such as roads, hedges and dykes. In the absence of these the presence of a marginal tramline was used to distinguish a field. The area of each field was calculated from 1:25000 Ordnance Survey maps. The percentage area lodged per field was estimated by visual assessment of the photographs with the aid of a stereoscope. Lodging was defined as an area of crop which could be distinguished as being near horizontal to the soil surface. Individual lodging events were not recorded. The marginal area of each field was defined by the width of the marginal tramlines. A split field was recorded when evidence of an old field boundary could be seen which had resulted from the amalgamation of two or more fields.

Table 2.1. Summary of the data for each target farm, and their surrounding areas

Site name	Code	County	Total area *ha*	Field No	Mean field size *ha*	Soil type	clay *%*	photo *date*
Arthur Rickwood	AR	Cambs	188	34	5.5	peat	0	20/7
Terrington	TR	Norfolk	223	61	3.7	silt	30	20/7
Gleadthorpe	GD	Notts	9	2	4.5	sand	10	20/7
Bridgets	BG	Hants	273	23	11.9	chalk	10	28/7
Kirton	KT	Lincs	385	15	25.7	sand	10	20/7
South Petherton	SP	Somerse	476	117	4.1	silt	10	28/7
Odiham	OD	Hants	427	29	14.7	clay	30	22/7
Boxworth	BX	Cambs	837	52	16.1	clay	60	25/7
Rosemaund	RM	Here	45	7	6.4	silt	30	20/7
Total/mean			**2865**	**340**	**8.4**			

Figure 2.1 shows that the data were taken from the east, south and west of England, with the sites encompassing a wide range of soil types including sand, silt, loam, clay and peat mixtures. The clay content of each soil type was estimated using the "Triangular diagram of soil textural classes" (White, 1987). The clay content varied from 0-10% for peat and sand soils to 30% or more for loams and clays. The site areas varied from 9 ha at Gleadthorpe to 838 ha at Boxworth. The number of fields surveyed at each site varied from 2 at Gleadthorpe to 117 at South Petherton. In addition, there was a large variation in the average field size from 3.7 ha at Terrington to 25.7 ha at Kirton. Dates of the photographs varied from the 20th to 28th July 1992; in the comparisons of sites, it has been assumed that no lodging occurred between these two dates.

2.2.1.2 Detailed subset

Data recorded

A subset of detailed data was generated from the fields belonging to the ADAS farms; this included information on crops affected by commercial husbandry and by trial treatments. In addition to the data recorded in the general dataset the detailed subset included total N applied, date of sowing, soil P, K, Mg, organic matter content, pH, previous crop 89, 90, 91, cultivation, PGR date and rate, harvest date and grain yield.

As shown by Table 2.2 the percentage of each site which was part of the ADAS farm was usually small, between 8 and 15%. ADAS Rosemaund was the exception where only the ADAS fields were studied. The site at Boxworth with 129 ha accounted for over half of the detailed subset, with the size of the other sites all being less than 50 ha. Crops were generally sown in September, apart from Terrington and Rosemaund where sowing extended to mid-October. Thirteen varieties of winter wheat and one autumn sown spring wheat were included in the survey, of which most were first wheats. PGR application was in April for all sites and was applied to most fields except those with lighter soils. The final yield was similar for all sites, ranging from 7.0 to 7.7 t ha^{-1}.

Table 2.2. Summary of the detailed data

Site name	Area (% of site)	Number of fields	Total area (ha)	Average field size (ha)	Mean grain yield ($t\ ha^{-1}$)
A. Rickwood	7.9	5	15	3.0	7.3
Terrington	13.2	6	30	4.9	7.0
Bridgets	9.5	2	26	13.0	7.7
Boxworth	15.5	11	129	11.8	7.2
Rosemaund	100	7	45	6.4	7.7
Total/mean	**29**	**31**	**244**	**7.9**	**7.4**

Site name	Date of sowing		PGR application date		Date of harvest	
	earliest	*latest*	*earliest*	*latest*	*earliest*	*latest*
A.Rickwood	15-Sep	30-Sep	07-Apr	08-Apr	06-Aug	29-Aug
Terrington	01-Sep	15-Oct	19-Apr	21-Apr	05-Aug	21-Aug
Bridgets	07-Sep	18-Sep	19-Apr	21-Apr	NA	NA
Boxworth	02-Sep	28-Sep	02-Apr	09-Apr	29-Jul	07-Aug
Rosemaund	01-Sep	20-Oct	03-Apr	23-Apr	NA	NA

The peat at Arthur Rickwood showed a very different soil analysis when compared with the other sites (Table 2.3). It had a lower pH, a much greater organic matter content, and a smaller application of N. Phosphorous (P), Potassium (K) and Magnesium (Mg) contents were similar to the other sites.

Table 2.3 Soil analyses for the detailed subset taken as an average of all fields at each target site;

Site name	Soil type	pH	Organic matter %	Total N applied *Kg ha^{-1}*	Soil P *Index*	Soil K *Index*	Soil Mg *Index*
Arthur Rickwood	peat	6.6	25	60	3.0	3.0	2.4
Terrington	silt	8.0	2.6	226	2.8	2.7	4.5
Bridgets	chalk	8.0	4.7	180	2.5	2.5	1.5
Boxworth	clay	7.8	3.1	176	2.1	2.5	2.4
Rosemaund	silt	6.9	2.9	136	3.3	2.6	2.9

Meteorological data

Daily rainfall (mm) and average wind-speed (knots) were obtained for all the sites for the May to August period with the corresponding 30 year long term means (LTMs) (*pers. comm*. R. Weightman).

Soil water content of the top 50 mm

As soil strength decreases rapidly with increasing water content (Payne, 1988) it was decided that a reasonable guide to lodging risk due to root failure would be to calculate when the top 50 mm of soil was at field capacity. During the greatest lodging risk period of June and July in this season it is likely that the soil water content of the top 50 mm will have varied between permanent wilting point (PWP) (assuming evaporation cannot dry the soil any further) and field capacity (FC). The quantity of water in the whole profile was likely to have been small because the very dry June of 1992 commonly produced soil moisture deficits of up to 100 mm in 600 mm of soil. This meant that once the top 50 mm had reached field capacity any more rain could be assumed to drain into a lower profile. The amount of water required to take a soil from PWP to FC, the available water capacity (AWC), was estimated for the top 50 mm of each soil type using data from Payne (1988); peat and silt soils required 10 mm, clay 8.3 mm, and sands 6.7 mm. To calculate the water content of the top 50 mm required the daily rainfall and evapo-transpiration rate. Daily rainfall data were used for June and July and it was assumed that the top 50 mm was at PWP on the 1st of June. An evapo-transpiration rate of 3 mm per day was used, which is the average of a wheat crop during its main growth period (Austin and Jones, 1975). It was also assumed that no evaporation loss occurred directly from the soil with all water being lost from the soil via the plant. When calculating the cumulative loss or addition of water to the soil profile it was assumed that evapo-transpiration occurred before a rainfall event as meteorological data are read in the morning and evapo-transpiration has occurred in the light hours of the previous day.

2.3 RESULTS

2.3.1 Spatial effects

The aerial survey covered 340 fields covering 2865 ha and involved 9 farms with their surrounding areas (see Figure 2.1 for site locations). Table 2.4 shows that on average 91% of the fields surveyed experienced some lodging. This resulted in 16% of the wheat area lodged. Of the lodged fields, 95% experienced lodging in the field margin, but only 2% experienced lodging in the tramlines.

Table 2.4. Summary of the site data

Site name	Total area		Fields with lodging		Area lodged		Margins lodged	Tram-lines lodged
	No of Fields	*Area/ ha*	*No of fields*	*% of fields*	*ha*	*%*	*% of lodged fields*	*% of lodged fields*
A. Rickwood	34	188	30	88	30	16	93	0
Terrington	61	223	56	92	19	9	98	5
Gleadthorpe	2	9	1	50	0.4	4	100	0
Bridgets	23	273	22	95	78	29	95	0
Kirton	15	385	12	80	38	10	92	0
S. Petherton	117	476	109	93	123	26	85	4
Odiham	29	427	25	86	68	16	96	4
Boxworth	52	837	47	90	101	12	98	4
Rosemaund	7	45	7	100	9	20	100	0
Total / mean	**340**	**2865**	**309**	**91**	**447**	**16**	**95**	**2**

Figure 2.2 shows that a large proportion of fields experienced small amounts of lodging and fields with severe lodging were less common. Thus, a quarter of fields had less than 5% of their areas lodged, half the fields had less than 10% of their areas

lodged, and three quarters of fields had less than 30% of their areas lodged. Ten percent of fields experienced a greater than 50% area lodged. This pattern was generally repeated for all sites (see for example data for South Petherton (Figure 2.3). At each site the percent area lodged of each field commonly varied between 0 and 90% (Figure 2.3). This was an important finding which demonstrated how lodging severity could vary at individual sites, even though each field probably experienced similar weather conditions.

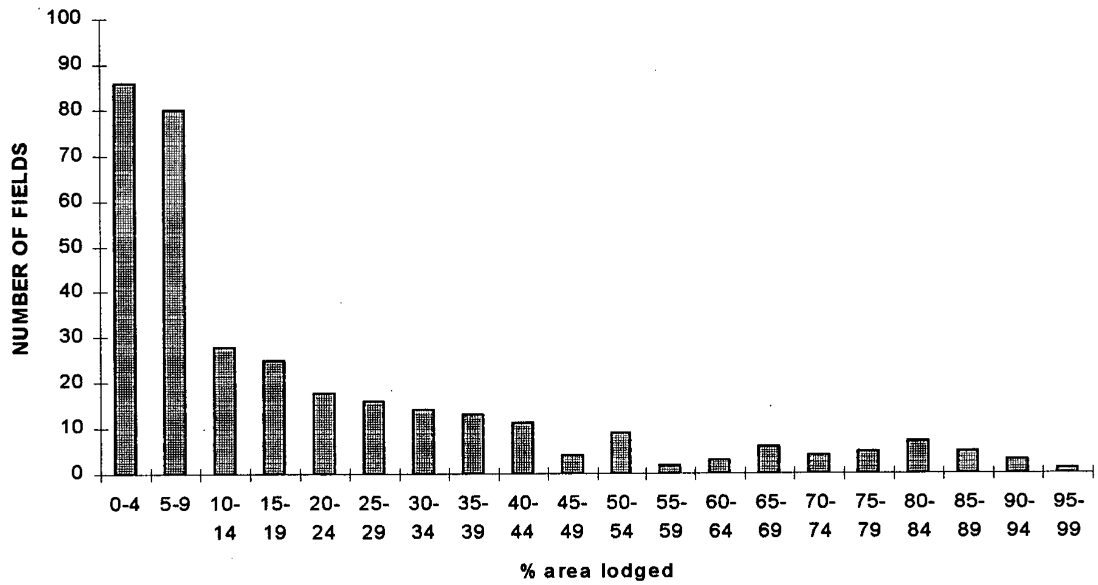


Figure 2.2 The number of fields which experienced different degrees of lodging at all sites combined.

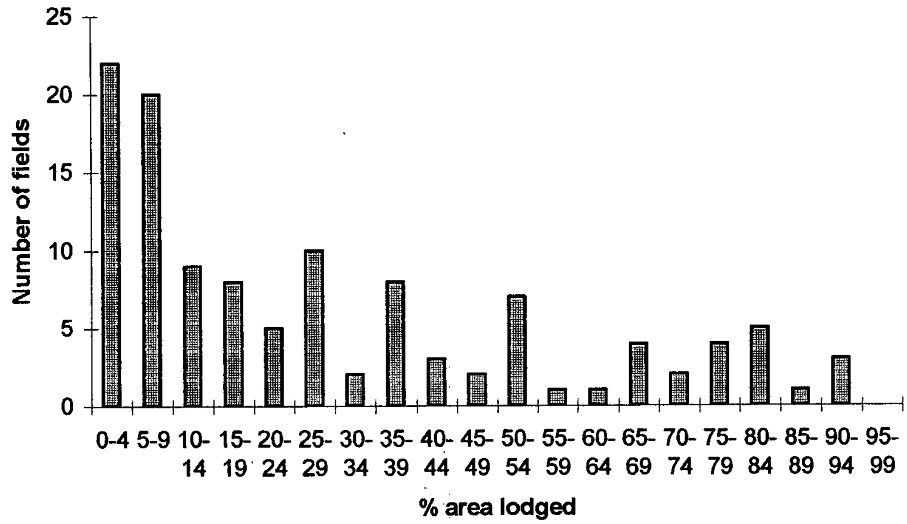


Figure 2.3 The number of fields which experienced different severeties of lodging at South Petherton.

2.3.1.1 Within fields

Distinct patterns of lodging within each field could be recognised for different lodging severities. For a low severity of 0 to 10% the lodging was usually confined to the margin and often involved the junction between the margin with the main body of the field. For fields with moderate amounts of lodging (10 to 50%), most of the margin was lodged with the lodged area extending into the central part of the field, between the tramlines. Occasionally a localised region of the field experienced severe lodging whilst the rest of the field, apart from the margin, was not lodged. For severe amounts of lodging (greater than 50%) most or the entire margin was lodged with lodging occurring evenly over the rest of the field, leaving the tramlines standing.

2.3.1.2 Between fields

Field size

Lodging has been found to occur most often in the field margin. It therefore seems reasonable to expect the percent area lodged in a field to be related to its size, with smaller fields having a larger proportion of lodged area, related to their larger proportion of marginal area to total area. The average percentage area lodged was constant at about 20% for all field sizes up to 10 ha. This average then decreased to between 14 and 15% for fields greater than 10 ha (Figure 2.4). Regression analysis for the percentage area lodged on field size showed a statistically significant trend ($P<0.05$) for a smaller percentage area lodged with larger field sizes.

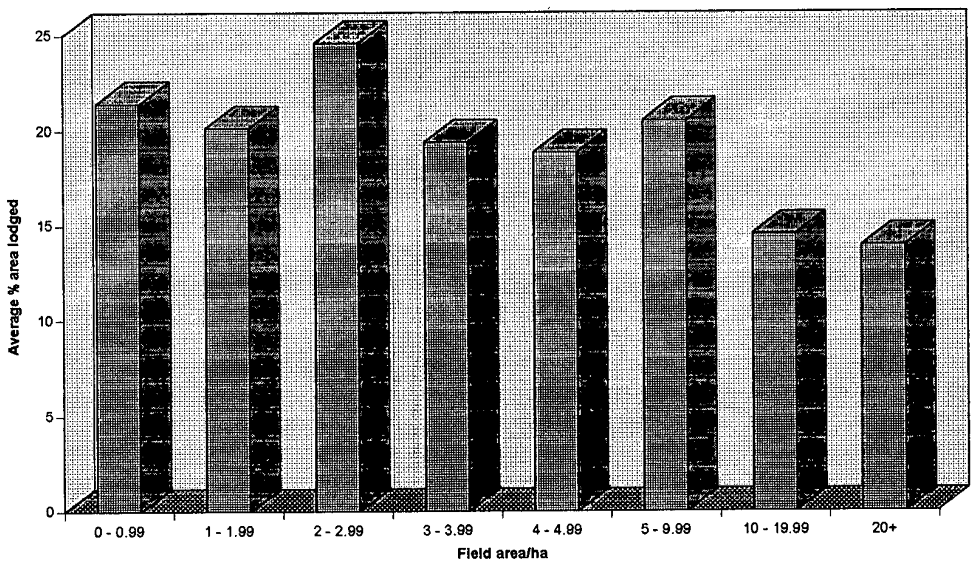


Figure 2.4 Average percent area lodged for different field sizes

Soil Type

Most lodging data was collected for the clay, silt, sand, clay loam and silt clay loam soils. A one-way ANOVA for percent area lodged on the five main soil types showed that lodging severity varied significantly ($P<0.05$) with soil type. Silt soils experienced the greatest lodging and clay and sand soils the least. The 106 silt fields had on average 25% area lodged. The 58 clay and sand fields each averaged about 10% area lodged.

2.3.1.3 Between localities

The four sites with the least percent area lodged were Gleadthorpe, Terrington, Kirton and Boxworth, all in the East Midlands and East Anglia. The three sites showing most lodging were Rosemaund, S. Petherton and Bridgets, all in the south and south-west of England. These results suggest that geographical position could influence lodging, with a lower lodging risk in east England than south west England. This could be due to a number of factors including differences in rainfall, average wind-speed, soil type and length of growing season.

Weather

Average or below average rain fell at all sites in June and approximately double the average rain fell at most sites in July (Table 2.5). However, variation in the monthly rainfall between sites was not related to variation in the percent area lodged at each site. A slight trend was found for greater lodging with greater maximum June day rainfall (Table 2.5). However, this was made less significant by the large amount of rain falling at the site with least lodging (Gleadthorpe) and by the small amounts of rain recorded at site with most lodging (Bridgets). The maximum July day rainfall varied from 19 mm at Rosemaund to 37 mm at Kirton and showed no correlation with the percent area lodged at each site.

Table 2.5 Summary of June and July rainfall at all sites

Site	June rain/mm	% of long term mean	Max June rain day /mm & date		July rain/mm	% of long term mean	Max July rain day /mm & date	
AR	27	51	9	19th	88	208	26	20th
TR	12	24	5	4th	92	269	29	20th
GT	62	111	32	30th	81	251	21	3rd
BG	53	99	32	30th	61	150	19	20th
KT	19	36	6	4th	109	374	37	20th
SP	50	102	25	30th	49	99	17	3rd
OD	32	63	9	19th	66	160	29	20th
BX	19	38	13	4th	69	204	27	20th
RM	45	82	15	9th	85	202	19	20th

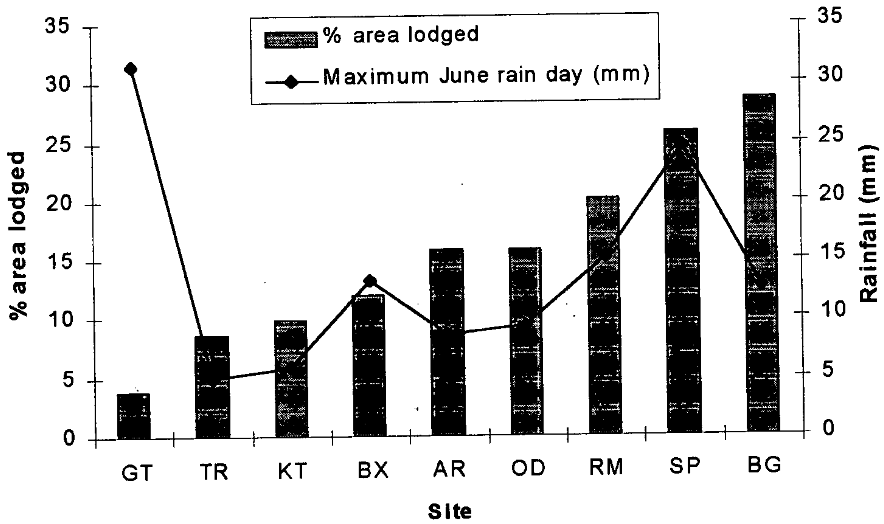


Figure 2.5 Maximum June rain day plotted against the percent area lodged for each site.

Table 2.6 shows the average monthly wind-speed in June and July, maximum wind-speed days in June and July and the wind-speeds during the three wet periods of 30 June, 8-14 July and 20 July. There was no relationship between the average wind-speed in June and July with the percentage area lodged at the different sites. In addition, these monthly averages were very similar to the long-term means. The maximum June wind-speeds occurred during the 4-5 and 16-20 periods, both of which were usually dry. The maximum July wind-speeds occurred during the 4-5 and 17-18 periods which were soon after rainfall events and may have contributed to lodging. The 8 to 14 July wet period had slightly higher wind-speeds than average, which again may have contributed to lodging. The wind-speeds during the 30 June and 20 July wet periods were less than the monthly averages.

Table 2.6 Wind-speed data for June and July and for the potential lodging periods

Site	June av. wind spd m/s	Max. June wind spd & date	Wind spd on 30 June	July av wind spd m/s	Max July wind spd & date	Av. wind spd 8-14 July	Wind spd on 20 July
GT	1.9	5.8 5th	1.9	1.9	5.1 5th	5.1	2.4
TR	2.5	5.8 14th	1.1	2.7	5.0 1st	3.8	2.5
KT	3.1	5.1 5th	1.6	2.7	5.7 5th	3.5	2.3
BX	1.9	4.2 18th	0.7	2.6	5.5 18th	3.2	2.5
AR	2.3	4.2 19th	1.1	2.5	4.8 17th	3.9	2.1
OD	4.0	8.6 20th	2.7	4.9	7.7 5th	8.6	3.1
RM	1.9	3.9 9th	2.0	1.8	4.0 4th	2.2	2.0
SP	3.8	8.2 16th	2.3	4.0	6.8 5th	6.8	1.6
BG	2.0	4.5 19th	2.9	2.4	4.6 4th	3.0	1.5

Three main periods can be observed when the top 50 mm of soil was at field capacity and would be expected to cause poorly anchored plants which were prone to root lodging. These occur between 30 June and 4 July (mainly the 30 June), 8 to 14 July and on the 20 July (see Figure 2.6 as an example). If root lodging was the cause of the majority of lodging in 1992 then it is likely that lodging occurred during one of these wet periods when the soil was at field capacity. The first wet period between the 30 June and 4 July was the most likely candidate for lodging because most of the sites either reached field capacity or were close to it during this period. Also the sites with most lodging such as S. Petherton and Bridgets (Figure 2.6) experienced the longest period at field capacity during this period. In addition, a high wind speed was often encountered soon after this wet period on the 4 or 5 of July (Figure 2.6). when the soil was still relatively wet and weak. Lodging was unlikely to have occurred in the middle wet period because this was often quite dry at some of the sites with greatest lodging. The last wet period is also an unlikely candidate because it occurred very close to harvest when the above ground fresh weight of the crop has greatly decreased, thus causing the crop to be less lodging prone.

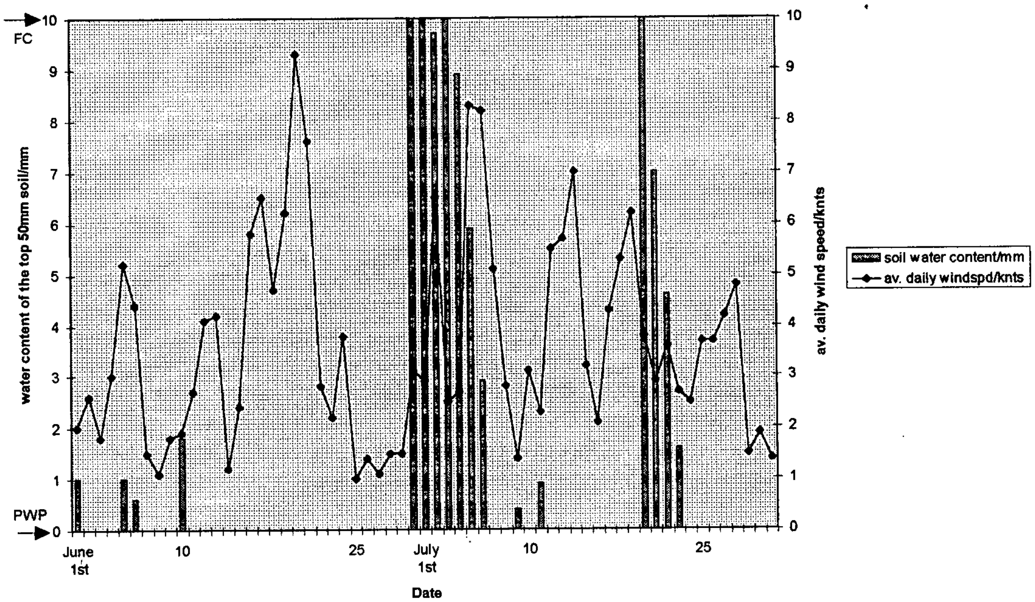


Figure 2.6 Daily water content for the top 50mm of soil between PWP and FC with the average daily wind-speed at Bridgets

2.4 DISCUSSION & CONCLUSIONS

Results from the aerial survey can be summarised as follows :

- 309 out of the 340 fields (91%) experienced some lodging.
- 456 ha out of 2865 ha were lodged (16%).
- 95% of the lodged fields contained lodging in the field margin.
- 2% of the lodged fields contained lodging in the field tramlines

The survey has produced the first estimate of the amount of lodging which occurs in the UK during seasons of severe lodging. This has enabled the cost of lodging to the farming industry to be calculated at £130 million in seasons with widespread lodging (Chapter 1). It is likely that the estimate of lodging underestimates the true UK average since the survey did not include the north of England, Scotland or Northern Ireland. In addition, the percent area lodged for other cereals such as winter barley and oats is likely to be greater still.

One of the most striking findings was that nearly all lodged fields had lodging in the boundary between the field margin and the main body of the field. It was from this area that lodging often appeared to spread to other parts of the field, probably by a 'domino' effect. This identifies the most lodging prone part of a field at which lodging controls should be targeted. Overlapping drilling and/or overlapping N applications may cause the high lodging risk of this area of the field. The importance of marginal areas in causing lodging was illustrated by smaller fields, which have a greater proportion of marginal area to total area, having a greater percent area lodged than large fields. This does not mean that growers should endeavour to reduce lodging by creating larger fields, more to concentrate on reducing the lodging risk of the marginal areas by reducing drill or spreader overlaps or targeting these areas with lodging controls. The lodging resilience of the crop next to the tramlines gives some ideas for how lodging can be avoided. It may be that lower plant density, sturdier plants (caused by brushing against spray vehicles) or compacted soil confer these plants to be more lodging resistant.

Within each locality or farm the percent area lodged in a field could vary from 10% to 90%. Assuming these fields had the same weather this suggests that the crop itself is very important in determining lodging risk. Different husbandry decisions described in Chapter 1 probably cause these differences in the crop. This adds to confidence that lodging can be controlled even in lodging conducive weather. No relationship was found between rainfall and wind-speed and the severity of lodging at different sites. It appears that quite unexceptional weather conditions at some sites were sufficient to cause widespread lodging. This supports work by Easson *et al.* (1993) who observed wind speed to be relatively unimportant in causing lodging and for lodging to be more closely associated with the occurrence of rainfall than the amount.

The greatest lodging was observed on sites in the South and South West and least in sites in the East of the country. This trend was not due to wetter conditions in the South West but may have been due to smaller field sizes or soil type. Most lodging was experienced by crops grown on silt which was the predominant soil type of the sites with most lodging in the South and South West. Silt soils are fertile and are likely to produce crops which are top heavy and lodging prone. They are also likely to have weak shear strength due to low clay content and high water retention which will reduce plant anchorage and increase the risk of root lodging. Sand soils experienced little lodging, probably due to the production of smaller crops and good drainage properties. Clay soils may have experienced less lodging because of their greater shear strength.

In summary, it has been shown that lodging risk is strongly determined by the state of the crop and soil type. The weather appears to be less important. This suggests that it should be possible to grow lodging resistant crops in most situations through careful crop management. It also suggests that if we can understand how plants develop and grow into crops which are either lodging prone or lodging resistant, then lodging risk could be estimated by assessing crops in the spring, in time for decisions on remedial controls.

3. CURRENT UNDERSTANDING OF LODGING

The first comprehensive review of lodging by Pinthus (1973) concluded that root lodging was generally the predominant type of lodging in cereals, caused by loss of anchorage after rainfall wetted up the soil. Pinthus (1973) described stem lodging as the bending or breaking of the lower stem internodes and that it was restricted to plants that are held tightly by a dry and hard upper soil layer. Root lodging was defined as straight and intact stems leaning from the crown, involving some disturbance of the root system, and that in moist soil the roots and crowns will give way to the turning moment created by the wind, which was often associated with the development of cracks in the soil (on the opposite side to the lodging).

In opposition to Pinthus, Neenan & Spencer-Smith (1975) argued that lodging in wheat was solely caused by stem breakage, except at the end of the season when root degeneration could possibly cause root lodging. They argued that during July root strength and root number were sufficient to prevent root lodging occurring, stating also that shearing of the soil that occurs in the windthrow of trees would not occur in cereals. Instead they established that resistance to bending was determined by Young's modulus (of elasticity) of the stem and the diameter of the stem, taking no account of any other canopy or soil parameters.

Graham (1983) broadly agreed with Pinthus (1973), that lodging was mainly caused by loss of anchorage as a result of failure of the soil surface, rather than by stem breakage or buckling. He also stated that the above ground morphological crop characteristics often associated with lodging could not be taken as causal but could alter the susceptibility of a crop to lodging.

Ennos (1991) and Crook and Ennos (1993) also suggest that stem lodging is relatively uncommon and that plants fail more often by root lodging. They studied in detail the mechanics of root lodging and found that anchorage of winter wheat is provided by a cone of rigid crown roots, emerging from the base of the plant. Crook and Ennos (1994) carried out experiments which showed that differences in anchorage strength between varieties were mainly due to the diameter of the root-soil cone, and also suggested that root lodging resistance might be improved by increasing both the angle of spread and the bending strength of the crown roots. Pinthus (1967) also indicated the potential value of crown root angle of spread as a possible indicator of lodging resistance.

Finally, Easson *et al.* (1993) observed the lodging process in more detail than had been previously achieved and concluded that lodging occurred slowly, over several hours and that stem buckling or breakage did not appear to be the principal form of structural failure. They also observed that lodging occurred mainly during or within 24h periods of rainfall, with wind speeds at crop height averaging 25 km/h (7 m/s) and gusting to 50 km/h (14 m/s), however, lodging also occurred following rainfall when wind speeds did no exceed 16 km/h (4.5 m/s). It was concluded that lodging was more closely associated with the occurrence of rainfall rather than the amount and wind speed was relatively unimportant.

3.1 CROP SIZE

In wheat, the force due to the wind acts primarily on the ear (during June, July and August) and induces a torque or turning moment, that increases down the stem and causes bending. Once a significant bending occurs, there is an additional turning moment due to the weight of the crop. Pinthus (1973) stated that torque is resisted by the bending resistance moment of the stem and by the plant anchorage in the soil, with the highest bending resistance moment being the straw strength.

Various components of crop size affect lodging risk. For example, varieties with large ears may be more prone to lodging, due to top heaviness and/or producing a large surface area for wind loading. Awned varieties e.g. Soissons may be particularly able to harness wind gusts, due to a larger surface area. A large canopy, possibly due to early sowing, high seed rate, excessive N applications may also predispose a crop to lodge. It may also trap more rainfall, increasing crop weight and therefore lodging risk. These varietal and husbandry effects on crop size, act to increase the bending moment exerted on the stem base and roots, during lodging conditions.

3.2 STEM FAILURE

The wind induced torque causes stem deformation (bending) and, up to a certain limit, this bending is reversible and the plant will resume its upright position, when the wind stops. The elasticity of the plant causes it to return to its original position after bending and, beyond the plastic limit, deformation will cause the plant to lean permanently i.e. become partially lodged.

Stem bending will be inversely proportional to the flexural rigidity or stem stiffness, given by EI (Young's modulus of elasticity x moment of inertia) for the stem material. It is important to remember that this is not a measure of stem strength, as stems may be stiff but weak because of a low elastic limit. A very stiff stem (large value of EI), may show little deformation and will transfer the torque operating on it to the root system therefore promoting root failure, if the soil conditions are appropriate. However, Pinthus (1973) states that low stem stiffness will increase stem bending and movement at the stem base, which may also promote root lodging due to the effects of these movements on the adhesion of roots in the soil.

3.3 ANCHORAGE FAILURE

When subjected to wind loading and/or rain loading the aerial parts of the wheat plant generate a force at the plant base which acts in parallel with the soil surface and a turning moment about it. If the plant is to maintain its upright position then these forces must be resisted, resulting in the formation of tensile, compressive and shear forces around the plant base and root-soil interface. Therefore, anchorage failure might occur due to roots breaking or stretching, or due to roots slipping through soil, or due to soil failure.

Crown root strength is relatively high (Graham, (1983) and Ennos, (1991)) and is unlikely to be exceeded by weather forces conducive to lodging. Therefore initial failure is more likely to occur due to failure of the soil particles adhering to the crown roots (resulting in roots slipping though the soil) or loss of anchorage due to soil deformation. Crook and Ennos (1993) have shown that anchorage of winter wheat is provided by a cone of rigid crown roots, emerging from the base of the plant. During root lodging this cone rotates at its windward edge below the soil surface, the soil inside the cone compressing the soil beneath. Both Pinthus (1967) and Ennos (1991) provide evidence for a correlation between the angle of crown root spread and lodging resistance in wheat. It is suggested that if crown root spread is poor (a small angle), the volume of soil occupied by the roots is low and therefore prone to shearing and rotational forces. However, if crown root spread is good (a large angle), a greater volume of soil is trapped and the shape of the root-soil plate will be more conducive to resisting rotational forces applied to it.

A prostrate growth habit may be associated with high tillering plants, particularly in low density plant populations. This may result in a wide stem base and a wide angle of crown root spread in the soil, both of which will be beneficial to plant anchorage and support. It is sometimes possible in high tillering varieties for the internodes arising directly from the crown to orientate parallel to the soil surface, with the stem only achieving a vertical orientation at a higher node. If this occurs, these stems may be better able to resist the compressive forces generated by wind and/or rain loading on the aerial parts, on the leeward side by leaning on the soil surface (Easson *et al.* 1992). Tillering may also be encouraged by light spring grazing, or rolling to bruise the crop. Prolific tillering (and a high tiller survival) may be likely to initiate a greater number of crown roots than varieties with a low tiller production and therefore they may have better anchorage capabilities.

Many growers suggest that drilling depth will alter the plants ability to resist lodging. However, the depth of drilling may not actually alter the relative depth of the crown itself, except for very shallow drilling circumstances. Austin and Jones (1975) suggest that complex responses to light and carbon dioxide form part of an integrated control system by which the seedling can adjust its growth pattern to compensate for variations in sowing depth, so that the crown is formed about two centimetres below the soil surface. Shallow drilling should result in the crown root structure being formed nearer the soil surface, which may as a result be less likely to withstand the forces subjected to it, than with the conventional or deeper drilling. For the deep drilling, the prolonged extension of the sub-crown internode (in order to lift the crown towards the soil surface) may result in a type of 'double-anchorage', where crown roots maybe initiated from close to the seed in association with a coleoptile tiller and from the crown nearer to the soil surface.

3.4 SOIL FAILURE

Soil shear strength is the internal resistance of soil to external forces causing two adjacent areas of soil to move relative to each other. Shear strength is a function of two types of force between soil particles, coherence (intergranular friction) and cohesion between soil particles. Coherence (intergranular friction) is the primary attractive force when soil is dry. As the moisture content in the soil increases, moisture films form and cohesion, caused by surface tension, becomes the predominant force governing soil shear strength. Cohesion is highly dependent on soil moisture content and is the major component of shear strength in wet clay soils at the plastic or liquid state. Small changes in cohesion have a much greater effect on the total shear strength than a proportionate change in intergranular friction (ADAS, 1982). It is therefore cohesion which will be the important factor during root lodging events, when the soil tends to be moist or wet.

Cohesive forces and soil shear strength is determined by soil texture, soil moisture content and bulk density (compactness). Clay soil types are perceived to have greater shear strengths. As soil moisture content increases soil shear strength decreases. Soils which are compacted (large bulk density) are stronger, but may inhibit root growth and actually reduce root anchorage. Factors which affect soil shear strength interact e.g. as the soil moisture content increases, the sensitivity of shear strength to changes in bulk density increases.

Soils with a low shear strength will slake and cap when liquid as a result of raindrop impact, whereas high strength soils at the liquid limit or above exhibit smearing (ADAS, 1982). It may be important to consider the soil consistency at the lodging event i.e. whether the soil is near its plastic or liquid limit, as these can be determined for a range of soil types.

Davies (*pers. comm)* suggests that cracking of the soil surface is important in terms of soil-water flow and infiltration rates in July. In a dry, cracking soil water entering will break up the clay into smaller peds, therefore decreasing the bulk density and shear strength. Cracking may also lead to uneven wetting fronts due to water infiltrating the cracks more readily than the uncracked soil surface. Cracking will also produce localised areas of low soil strength around the point of root anchorage which may lead to lodging.

The condition of the seedbed (when the crop is drilled) is likely to influence the initial growth and position of the seed in the soil, which could later affect its structural support. A fine, even seedbed with a good crumb structure may be better than a cloddy, uneven seedbed, which could be detrimental to the initial anchorage and crown root development of the plant. Davies (*pers comm)* suggests that if the soil surface is loose i.e. due to the formation of a surface tilth during wetting and drying cycles in the summer, soil strength will be weak.

3.5 SUMMARY

Lodging results from a failure in either the soil, root, or shoot or a combination of these. Many interrelated attributes predispose a particular crop to lodge or remain upright, such as :

a) soil strength in the surface layer (highly dependent on soil texture & moisture content).
b) crown rooting pattern and structural integrity.
c) crown depth which depends on sowing depth and seed treatment e.g. Baytan.
d) stem thickness and strength, particularly of the lower internodes.
e) stem length and weight distribution which affect the leverage on the stem base.
f) crop canopy structure which affects air movement and rain-trapping.
g) field exposure, affecting wind speeds.
h) location, which governs soil type and patterns of rainfall.

This list illustrates the complexities which may act to confer lodging. Despite this we believe that the majority of growers perceive lodging to be caused by stem failure alone. It is our belief that both stem and root lodging can predominate given the appropriate soil and crop conditions. In moist or wet soil conditions we predict that root lodging is most likely to occur, but if the soil becomes very dry (which greatly increases soil shear strength) or if rooting is particularly strong, stem lodging is likely to predominate. We also believe that the widespread, severe lodging in a year such as 1992 is likely to be caused predominately by root failure as lodging across the UK was associated with higher than average July rainfall. Buckling of the stem (generally in the lower internodes) is an important form of lodging which occurs on a more localised basis, often associated with inaccurate crop management e.g. over-fertilising with N, or where the drill or fertiliser spreader caused overlapping on patches of crop around the inner headland edge. Disease e.g. eyespot also causes stem lodging and may act as a catalyst for other types of lodging.

The literature reviewed here illustrates that there is not one simple answer to the lodging problem, with stem or root lodging possible in different circumstances. Crook and Ennos (1993) have greatly improved understanding of the root component involved in lodging. While Easson *et al.* (1993), have gone some way into considering all the possible components involved during lodging, they were not able to successfully model the lodging process to the extent required to benefit growers and the industry as a whole. It is therefore our aim to try and achieve a fuller understanding of the lodging process. By using current knowledge and field experimentation we aim to model and predict the process to improve perception of lodging risk throughout the industry.

4. A MEANS OF CALCULATING LODGING RISK

4.1 INTRODUCTION AND RATIONALE

It is clear that lodging risk is affected by both weather and husbandry. We envisage that much of the influence of these factors on lodging risk is through their ability to alter crop structure but, to date, few studies have been carried out which interrelate the facets of structure that alter lodging risk. The interactions between weather, cultivar, and husbandry appear to confer a complexity on the lodging process that makes a proper understanding of its control very difficult.

In this chapter an attempt has been made to understand these complex interactions through the development and calibration of a model describing the lodging process. The model assumes that the dominant parameter that affects lodging is the wind induced bending moment at the stem base. The value of this bending moment relative to the failure moment of the stem, and the failure moment of the root/soil system indicates whether or not stem or root lodging will occur. A fundamental assumption is made that the unit of stem lodging is the individual shoot, and that the unit of root lodging is the whole plant.

When suitably calibrated, the model should enable quantitative predictions of lodging risk to be made. The ultimate figure that is arrived at is the probability that lodging will occur in any one lodging season (a period of six weeks from late June to early August). However, it needs to be appreciated at the outset that the model contains a number of assumptions of different types. Thus the "answers" that are produced should not be regarded as accurate on an absolute basis (and indeed could not be shown to be because of their probabilistic form, except through field experiments lasting many years). The model does however have significant uses - in particular as a framework for identifying the major site, weather, soil and crop parameters that are important in the lodging process, and as a tool for enabling the relative effects of different agronomic treatments to be understood. What follows should be viewed in this light.

In section 4.2 an outline of the method is presented. This is followed in section 4.3 by a detailed description of the various components of the model. Section 4.4 presents a parametric investigation in which the various model parameters are systematically varied to enable their effects to be determined. Finally, concluding remarks are made in section 4.5.

4.2 OUTLINE OF THE METHOD

A flow chart of the lodging risk assessment method is given in Figure 4.1. The overall aim of the method is to predict the probability of stem lodging and root lodging at any one site in a particular lodging season. For the site in question it is necessary to provide data on the wind, rain, soil and expected plant characteristics during the peak lodging period in July. The daily maximum hourly mean wind speed and daily rainfall probability distributions are then calculated from the wind and rainfall characteristics of the site. A Monte Carlo simulation technique is then used to generate a series of 1000 hourly mean wind speeds and daily rainfalls that are consistent with the calculated probability distributions. For each wind speed/rainfall data pair, the degree of soil saturation, soil shear strength and plant natural frequencies are then calculated, these parameters being fundamental in determining the plant's dynamic characteristics and lodging resistance. The method of Baker (1995) is used to calculate the extreme stem base bending moment that would be expected with the simulated wind and rain conditions. The stem failure moment and root failure moment are calculated using simple principles of structural analysis and a simplified version of the root strength model of Crook and Ennos (1993). A comparison of these three moments then enables the occurrence of stem and root lodging to be ascertained for each wind speed/rainfall data pair. The total number of occurrences of both lodging types is then divided by 1000 to give a probability of lodging for any one day. The probability of lodging during any one lodging period (40 days centred on mid July) is then calculated. The individual components of the method are considered in more detail in the next section.

1) Input wind speed and rainfall characteristics for July

↓

2) Input soil and plant characteristics expected in July

↓

3) Determine daily wind speed and rainfall probability distributions

↓

4) Generate realisations of wind speed and rainfall probability distributions to represent weather conditions in any one day in July

↓

5) Calculate soil saturation, soil shear strength and plant natural frequency

↓

6) Calculate extreme stem base bending moment

↓

7) Calculate stem failure and root failure moments

↓

8) Ascertain the occurrence of stem and/or root lodging

↓

9) Repeat steps 4 to 8 one thousand times

↓

10) Calculate the probability of lodging in any one day

↓

11) Calculate probability of lodging during 40 days centred on July

Figure 4.1 Outline of method for assessing lodging risk

4.3 COMPONENTS OF THE MODEL

4.3.1 Wind probability distribution and wind speed predictions

The first question that arises is what definition of wind speed should be used. As shown below the gust speed likely to cause lodging is calculated from the mean hourly wind speed. It will also be seen in the next section that it is appropriate to use daily average rainfalls to predict the ground conditions. Thus what is ideally required is the probability distribution of the maximum hourly mean wind speed that can be expected to occur in any one day. Data for this parameter is not directly available, but compilations of data are available for the probability distribution of hourly mean wind speeds at any one site and these can be used to attain the required distribution. The probability p_w that this hourly mean wind speed will exceed a certain value V is given by the Weibull distribution

$$p_w = e^{-k_1 V^{k_2}} \tag{4.1}$$

where k_1 and k_2 are site dependent constants. If, for the site in question, the value of V that is exceeded 50% of the time is V_{50} and the value that is exceeded 1% of the time is V_{99} one may write:

$$0.5 = e^{-k_1 V_{50}^{k_2}} \tag{4.2}$$

$$0.01 = e^{-k_1 V_{99}^{k_2}} \tag{4.3}$$

Thus if V_{50} and V_{99} are known, k_1 and k_2 may be found. Values of these velocities, ten metres above ground level in open countryside, at sea level conditions, V_{50}' and V_{99}', are given by various compilations of Met Office data (e.g. Cook (1985)). To attain values of V_{50} and V_{99} of relevance to the lodging problem, V_{50}' and V_{99}' must first be transformed with correction factors to allow for the difference between hourly mean wind speeds and daily maximum hourly mean wind speeds. They must then be further transformed to account for height above ground level, the altitude of the field in question (h m above sea level) and for seasonal conditions (i.e. July).

The expressions that are adapted are

$$V_{50} = 1.6 \text{ x } V_{5'0} \left(\frac{\ln(1/z_0)}{\ln(9/z_0)} \right) (1 + 0.0007\text{h}) \text{ x } 0.71 \tag{4.4}$$

$$V_{99} = 1.15 \text{ x } V_{9'9} \left(\frac{\ln(1/z_0)}{\ln(9/z_0)} \right) (1 + 0.0009\text{h}) \text{ x } 0.71 \tag{4.5}$$

The factors 1.6 and 1.15 transform the values of hourly mean wind speed to the equivalent values of daily maximum hourly mean wind speed, and have been attained by the authors from an analysis of several years data for a number of met. office sites. The logarithmic terms describe the well known logarithmic velocity profile and transform the velocity from a height of ten metres above ground level (or nine metres above the effective ground level, the top of a typical wheat canopy being one metre) to a value two metres above ground level (or one metre above the canopy top). z_0 is the surface roughness length. The reason for choosing to specify the velocity one metre above the canopy top is because it is known that wind loading of individual plants is due to large gusts from above the canopy penetrating through the top of the canopy. Thus it seems reasonable to specify wind gusts one metre above the top of the crop. The expressions in h represent the altitude corrections as given by Cook

(1985). The 0.71 factor, also given by Cook (1985), allows for the fact that wind speeds in July are significantly smaller than average annual values.

Once k_1 and k_2 have been determined from equations 1 to 5, a value of V, now interpreted as the daily maximum hourly mean wind speed, can be obtained from:

$$V = (-ln(p_w)/k_1)^{1/k_2} \tag{4.6}$$

and a randomly generated value of p_w between 0 and 1.

4.3.2 Rainfall probability distribution and rainfall and soil saturation predictions

The next question that arises is what rainfall period is relevant to the lodging process. Intuitively one would expect that lodging would be dependent upon both short duration high intensity rainfall (of about one hour), and also by long-term rainfall conditions (average monthly rainfalls). As a compromise the lodging model uses daily rainfalls as its basis for the determination of soil saturation conditions. Note firstly that antecedent soil moisture is not taken into account, on the assumption that the top few centimetres of soil, which are of relevance to lodging, dry out very quickly and are usually in a dry condition. Secondly no account is taken in the model of the effects of evapotranspiration in reducing the amount of moisture in the soil or of the effect of plant interception. It is assumed that during lodging periods, when the weather is usually overcast and wet, evapotranspiration will be small, and that over one day most of the rain that falls will find its way onto the ground surface.

Shaw (1983) shows that the probability of the average daily rainfall exceeding a value i is given by p_r, where p_r is given by:

$$p_r = e^{-k_3 i} \tag{4.7}$$

k_3 can be found from meteorological data for the daily rainfall that is exceeded 50% of the time, i_{50}, since:

$$0.5 = e^{-k_3 i_{50}} \tag{4.8}$$

Thus a realisation of the daily rainfall can be obtained from a randomly generated value of p_r between 0 and 1 and

$$i = -\ln(p_r)/k_3 \tag{4.9}$$

Once a value of i has been calculated, the surface layer of the soil is taken to be at field capacity if

$$i > l\,(f - w)\,\frac{\_{s}}{\_{w}} \qquad (4.10)$$

where l is the crop structural rooting depth, f is the soil water content by weight at field capacity, w is the soil water content by weight at the permanent wilting point, $\_{s}$ is the density of soil and $\_{w}$ is the density of water.

4.3.3 Determination of natural frequency

The natural frequency of the canopy/root system n, can be expected to be a function of the wetness of the soil, with n decreasing in wet conditions due to the loosening of the soil around the roots. On the basis of limited experimental data (*unpublished*) the value of natural frequency in saturated conditions n_W is taken as $k_4\, n_D$ where n_D is the value in dry conditions and $k_4 = 0.8$. For soil conditions between permanent wilting point and field capacity the method assumes that

$$n = n_D - \frac{i}{\frac{\_{s}}{\_{w}}(f - w)\, l}(n_D - n_w) \qquad (4.11)$$

4.3.4 Calculation of ground strength

The ground shear strength s for a wet soil at field capacity s_w is given by

$$s = s_w = (1484\, e^{-5f/c}) \left(\frac{76.7 - 8.39v}{76.7 - 8.39\, v_R}\right)\left(\frac{47c - 2.94}{47\, c_R - 2.94}\right) \qquad (4.12)$$

Here c is the clay content by weight and v is a visual score for soil structure (MAFF 1982), which is a measure of soil compaction in terms of the proportion of macro pores in the top 20cm of the soil. A soil with a visual score of zero has very few macro pores and is very compacted and strong. A soil with a visual score of ten has many macro pores and is uncompacted, friable and weak. c_R and v_R are 'reference' values of c and v. This equation was derived from a variety of sources. The term in the first bracket relating soil strength to water content at field capacity was derived from data collected during the experiments reported in Berry *et al.* (1998). Note that this data was all obtained for a clay content of 0.27. The second term relating soil strength to visual score is taken from MAFF (1982), whilst the third relating soil strength to clay content is taken from Guérif (1994). If reference values of v_R =5 and c_R = 0.27 are taken, equation 4.12 reduces to:

$$s = s_w = (1484\, e^{-5f/c})(2.20 - 0.24v)(4.82c - 0.30) \tag{4.13}$$

For dry soil at permanent wilting point *(i = 0)* the soil strength s_D is taken to be given by a similar expression

$$s = s_D = 1125\, e^{-5w/c}(2.20 - 0.24v)(4.82c - 0.30) \tag{4.14}$$

For values of *i* between 0 and l(f - w) $_s$ / $_w$ the shear strength is taken to be given by:

$$s = s_D - \frac{i}{\frac{\_s}{\_w}(f - w)\, l}(s_D - s_w) \tag{4.15}$$

i.e. a linear variation of s with i is presumed.

4.3.5 Calculation of stem base bending moment

Once values of V and n have been obtained the value of the base bending moment for one shoot can be obtained from the method of Baker (1995) for plants within canopies. This gives B as

$$\frac{B}{\frac{1}{2}\delta\, A C_D V_g^{\,2} X} = (1 + \frac{g}{(2\pi n)^2 X}(1 + e^{-\pi\delta}\frac{\sin(\pi/4)}{\pi/4}) \tag{4.16}$$

where ρ is the density of air, A is the ear area, C_D is the drag coefficient, X is the centre of gravity height of a shoot and δ is the plant damping ratio. V_g is a gust velocity and is related to the daily maximum hourly mean velocity *V* by the expressions of Greenway (1979)

$$\frac{V_g}{V} = 1 + \frac{\sigma_v}{V} L \tag{4.17}$$

where

$$L = J_1 g_v \tag{4.18}$$

and

$$g_v = \sqrt{2 ln(J_2 nT)} + 0.577 / \sqrt{2 ln(J_2 nT)} \tag{4.19}$$

$$J_1 = 1 - 0.1925((2n^x L_v / V) + 0.1)^{-0.6792} \tag{4.20}$$

$$J_2 = (n^x L_v / V)^{-1} (0.0066 + 0.2130(2n^x L_v / V))^{-0.6543} \tag{4.21}$$

σ_v/V is the turbulence intensity taken as 0.5 at the crop height (Finnigan, 1979), ^xL_v is the turbulence length scale at the height at which the velocity is specified (Finnigan, 1979) and T is the observation time of one hour. Equation (4.16) was derived on the basis that, over a wheat canopy, discrete coherent gusts (known as Honomi) are seen to occur that deflect the plants, which then oscillate backwards and forwards until the motion is damped out. The relationship between the mean and gust velocities (equation 4.17) is valid for gusts above a canopy only. The method assumes that the canopy penetrating gusts can be specified at one metre above the canopy top. This must be regarded as a reasonable if significant assumption.

4.3.6 Calculation of stem failure moment

The stem failure moment, B_s, can be calculated from the standard formula of structural analysis for a cylinder.

$$\sigma = B_s\, a/I \tag{4.22}$$

where σ is the failure yield stress of the stem material, a is the external radius of the stem base and I is the cross sectional second moment of area $\pi(a^4-(a-t)^4)/4$ where t is the wall thickness. Thus

$$B_s = \frac{\sigma \pi a^3}{4}\left(1-\left(\frac{a-t}{a}\right)^4\right) \tag{4.23}$$

Values of a, σ and t need to be specified. Note that σ is the failure yield stress in tension. This is unlike the approach adopted by Graham (1983) who assumed that failure occurs due to compressive buckling of the stem. Such an analysis is not appropriate for a slender, thick walled column such as the internodal length of a wheat stem, although it could be argued that it might be appropriate for failure at the solid stem nodes. However a simple comparison of predicted failure strengths reveals that tensile failure is the critical condition.

4.3.7 Calculation of root failure moment

The root failure moment B_R is given by the method of Crook and Ennos (1993) who showed that

$$B_R = k_5\, s\, d^3 \tag{4.24}$$

where d is the root cone diameter and k_5 is a constant. Crook & Ennos give a theoretical value of 3.5 for this parameter (for an overturning disk on a soil surface) but their experiments give a value of close to 1.0. However results of the experiments reported in Berry *et al.* (1998; Figure 4.2) where measured values of B_R (from mechanically loaded plants) were plotted against sd^3 suggest a much lower value of k_5 of 0.43. The difference between the experimental results and the results of Crook & Ennos are probably due to the different methods of measuring root cone diameter - by careful excavation of the entire root/soil system in the case of Crook & Ennos, and by analysis of washed structural roots in Berry *et al.* (1998). The value k_5 found by Berry *et al.* (1998) will be used because it was developed from a wider range of soil conditions than tested by Crook & Ennos (1993).

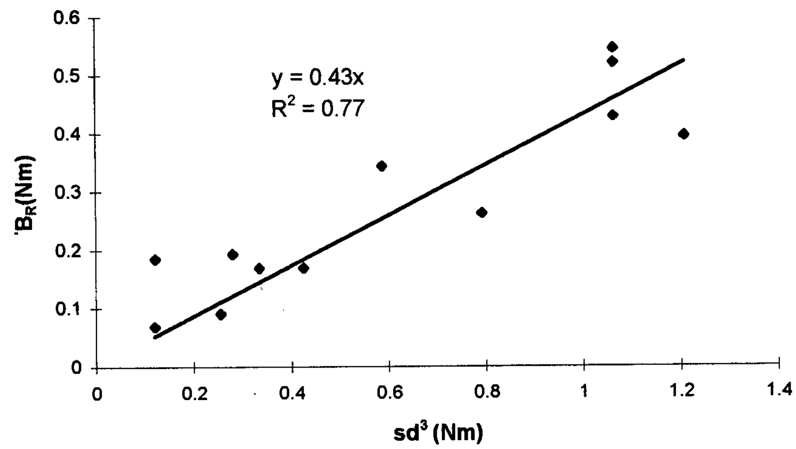


Figure 4.2 The product of soil shear strength and root plate diameter cubed (sd^3) plotted against root failure moment (B_R).

4.3.8 Calculation of lodging probabilities

For each pair of values of V and i, stem lodging is taken to occur if

$$B > B_s \quad \text{and} \quad NB < B_R \tag{4.25}$$

Root lodging is taken to occur if

$$B < B_s \quad \text{and} \quad NB > B_R \tag{4.26}$$

where N is the average number of shoots. Root and stem lodging together is taken to occur if

$$B > B_s \text{ and } \quad NB > B_R \tag{4.27}$$

Thus by summing the number of lodging incidents predicted and dividing by 1000 the stem only, root only, stem and root combined and total lodging probabilities (p_s, p_R, p_{RS}, p_T) can be found for any one simulation of met. conditions. To relate the probability p_T to the total probability of lodging occurring during any one lodging period (P_T) (40 days centred on July) the following formulae (based on elementary statistical principles) is used.

$$P_T = \Sigma_{i = 1 \text{ to } 40} \, u_I \tag{4.28}$$

where

$$u_i = p_T \; (1 - \Sigma_{k= 1 \text{ to } I-1} \, u_k) \tag{4.29}$$

and $u_o = 0$. This represents the probability of lodging occurring in any one year. The return period for a lodging incident T_T is given by $1/P_T$

4.4 PARAMETRIC ANALYSIS

In this section the model predictions for a set of standard parameters are considered in some detail. This is followed by the consideration of the results of a parametric analysis, that show the effects that variations in the different model parameters have on the predicted lodging risk. It should be noted that it is known that there are many interactions between the chosen parameters of the model, but the parametric analysis helps by identifying those parameters having the largest effect on lodging risk.

The standard parameters of the lodging model are shown in Table 4.1, together with the range of these values normally found in the UK, that will be assumed in the parametric analysis. When the model is run with these standard parameters, each of the individual realisations of wind speed and rainfall lead to realisations of base bending moment (B) and root failure moment (B_R).

Figures 4.3 to 4.7 show a number of histograms for the results of this case. Figures 4.3 and 4.4 show the probability distributions of daily maximum hourly mean wind speed and daily rainfall. These have the expected forms of the probability distributions given in equations (4.1) and (4.7). Figure 4.5 shows a histogram of soil strength realisations. It can be seen that whilst this histogram has a main peak for soil strengths between 40 and 50 kPa, there is a lower peak below 10kPa that represents the soil condition at field capacity. This peak occurs because the soil strength is assumed not to fall below its value at field capacity, even for very large realisations of rainfall. Figure 4.6 shows histograms of the base bending moment for all the shoots of a single plant (NB) and root failure moment (B_R). Only the lower tail of the latter histogram is shown - its main peak is actually at around 0.8 Nm, but a lower peak can be seen between 0.1 and 0.12 Nm due to the lower peak in soil strength values. It can be seen that these histograms overlap only to a small extent. It is for simultaneous realisations of NB and B_R in this overlap region that root lodging occurs (equation (4.26)). In fact for the standard conditions seven such realisations occur in 1000 realisations of wind speed and rainfall i.e. $p_R = 0.007$. Finally, Figure 4.7 shows the histogram of the base bending moment of a single shoot (B) together with the value of stem failure moment (B_S) which, being a function of stem parameters only, does not vary with wind and rainfall. It can be seen that, for these standard conditions, B is always less than B_S so stem lodging does not occur and $p_S = 0$ (equation (4.26)). Similarly $p_{RS} = 0$ for these conditions and thus $p_T = 0.007$. Thus it can be seen that the extent to which lodging is predicted depends upon the relative positions of the value of B_S and the histograms of B, NB and B_R.

Table 4.1 Ranges of the standard parameters expected in the UK.

Parameter	Notation	Standard value	Range of values for UK	Source
Fixed model parameters				
Turbulence length scale (m)	^xL_v	1.25	1.0 to 1.5	F79
Damping ratio		0.05	0.03 to 0.07	A
Observation time (s)	T	3600	1800 to 5400	A
Turbulence intensity	v/V	0.50	0.4 to 0.6	F79
Ear drag coefficient	C_D	0.3	0.2 to 0.4	G83
Meteorological and site parameters				
Hourly wind speed exceeded 50% of time (m/s)	V_{50}	4	3 to 5	C85
Hourly wind speed exceeded 99% of time (m/s)	V_{99}	10	8 to 12	C85
Daily rainfall exceeded 50% of time (mm)	i_{50}	2	1 to 3	S83
Site altitude (m)	h	50	0 to 200	A
Soil parameters				
Clay content (g/g)	c	0.25	0.2 to 0.4	R94
Visual score	v	5	2 to 8	M82
Water content at field capacity (g/g)	f	0.27	0.2 to 0.35	R94
Water content at permanent wilting point (g/g)	w	0.15	0.1 to 0.2	R94
Crop parameters				
Ear area (m^2)	A	0.001	0.0006 to 0.0012	B98
Centre of gravity height (m)	X	0.5	0.2 to 0.8	C94
Dry natural frequency (Hz)	n	1	0.5 to 1.5	G83
Number of shoots per plant	N	3	1 to 9	E93
Stem base radius (mm)	a	1.5	1 to 3	G83
Stem wall thickness (mm)	t	0.5	0.3 to 0.75	G83
Stem failure stress (MPa)		40	15 to 50	G83
Root plate diameter (mm)	d	35	10 to 80	C93
Rooting depth (mm)	l	35	15 to 60	B98

Key to sources: Author estimates based on A author estimate, B98 experiments reported in Berry *et al.* (1998), R94 Rowell (1994), C85 Cook (1985), C93 Crook and Ennos (1993), C94 Crook *et al.* (1994), E93 Easson *et al.* (1993), F79 Finnigan (1979), G83 Graham (1983), M82 MAFF (1982), S83 Shaw (1983).

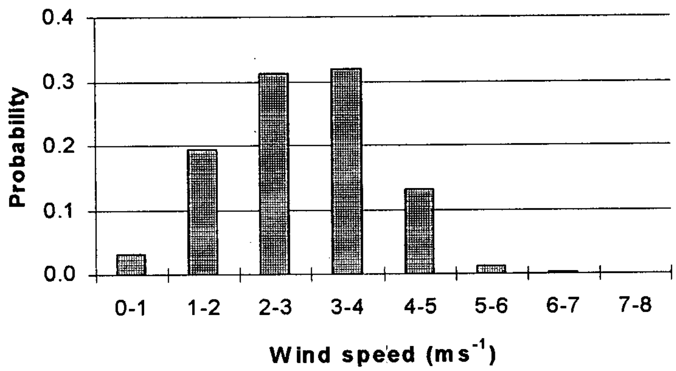


Figure 4.3 Probability distribution of the daily maximum hourly mean wind speed

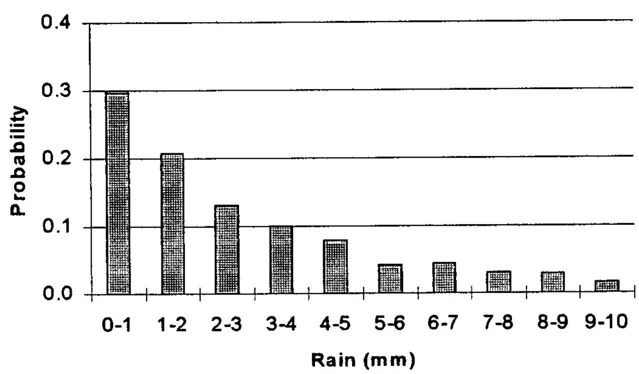


Figure 4.4 Daily rainfall probability distribution

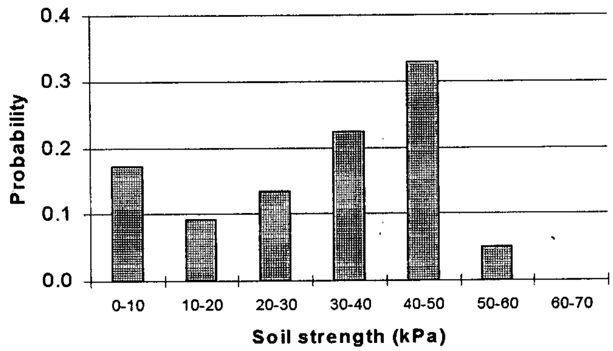


Figure 4.5 Soil strength probability distribution

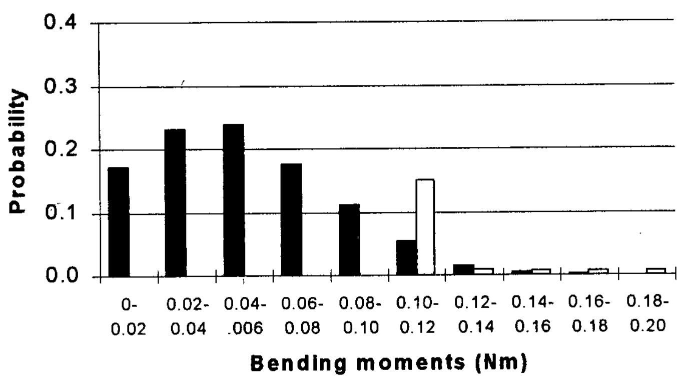


Figure 4.6 Shoot base bending moment x number of shoots (hatched bars) and anchorage failure moment (open bars) probability distributions

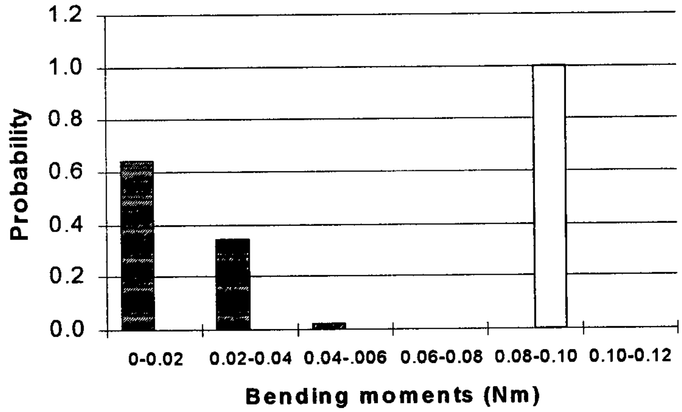


Figure 4.7 Shoot base bending moment (hatched bars) and stem failure moment (open bar) probability distributions

Now consider the results of the parametric analysis. The effect of varying each of the parameters defined in Table 4.1 over the ranges expected to occur in typical UK wheat crops will be demonstrated. The results of this analysis are shown in Table 4.2 which gives the overall lodging risk in a lodging season P_T for the maximum and minimum values of the individual parameters. Before discussing these results two points need to be made. Firstly, it must be noted that the value of risk varies in discrete steps - this is simply because the underlying probabilities for individual lodging realisations vary in discrete steps. For example the standard conditions shown in Table 1 give seven lodging events in a thousand realisations resulting in an overall probability for the lodging season of 0.245. If only six such events had been predicted, the probability would be 0.214 and if eight had been predicted the probability would have been 0.274. Secondly for variations in nearly all the parameters only root lodging is predicted and the variation of the lodging probability is monotonic with variations in the parameter. Thus in what follows the effect of variations in any of the parameters can mainly be judged simply by considering the lodging risk produced by the minimum and maximum values of the parameters i.e. from the results of Table 4.2. However where a very large variation in lodging risk is predicted over the parameter range, or where stem lodging occurs, or where the lodging risk variation is not monotonic, the results will be considered in more detail than presented in Table 4.2.

Table 4.2 Parametric analysis

Parameter	Seasonal lodging risk (P_T) at minimum parameter value	Seasonal lodging risk (P_T) at maximum parameter value
Fixed model parameters		
Turbulence length scale (m)	0.214	0.303
Damping ratio	0.303	0.245
Observation time (s)	0.214	0.274
Turbulence intensity	0.113	0.636
Ear drag coefficient	0.004	0.691
Meteorological and site parameters		
Hourly wind speed exceeded 50% of time (m/s)	0.213	0.589
Hourly wind speed exceeded 99% of time (m/s)	0	0.621
Daily rainfall exceeded 50% of time (mm)	0.077	0.407
Site altitude (m)	0.213	0.636
Soil parameters		
Clay content (g/g)	1	0
Visual score	0	1
Water content at field capacity (g/g)	0	0.716
Water content at permanent wilting point (g/g)	0.181	0.572
Crop parameters		
Ear area (m^2)	0	0.605
Centre of gravity height (m)	0.039	0.704
Dry natural frequency (Hz)	0.934	0.113
Number of shoots per plant	0	1
Stem base radius (mm)	0.996	0.245
Stem wall thickness (mm)	0.274	0.245
Stem failure stress (MPa)	0.979	0.245
Root plate diameter (mm)	1	0
Rooting depth (mm)	0.636	0.148

Consider first the fixed model parameters. Table 4.2 shows the effect on lodging risk of variations in turbulence length scale, damping ratio, observation time, turbulence intensity and drag coefficient. None of these parameters are well specified in the literature. The range given is purely illustrative, but the results predict only root lodging for variation in all these parameters, as was the case with the standard values. Table 4.2 shows that the variations of lodging risk with variations in turbulence length scale, damping ratio and observation time are gratifyingly small, and thus the fact that their values are not well known is not too important. However the results are sensitive to variations in turbulence intensity and drag coefficient. These two parameters are not well specified, and these results suggest that further experimental data are needed to specify these parameters more precisely.

Now consider the site parameters. Table 4.2 shows the effect of varying the hourly mean wind speed exceeded 50% of the time (V_{50}), the wind speed exceeded 99% of the time (V_{99}), the daily rainfall exceeded 50% of the time (i_{50}) and the site altitude (h) respectively. Again only root lodging is predicted. As expected an increase in wind speed or site altitude increases lodging risk. Variations in V_{99}, are most significant. Variations in i_{50} also produce a large change in the probabilities with an increase in root lodging risk as rainfall increases, as would be expected.

Now consider the soil parameters. Table 4.2 shows the effect of varying clay content, visual score, water content at field capacity and water content at the permanent wilting point respectively. Only root lodging is predicted, which is not surprising since, as the standard values did not show stem lodging, it is not expected that variations in soil parameters will affect this. The effects of variation in clay content and visual score are very large indeed, with overall lodging risks varying between 0 and 1 as the parameters are varied. Variation in water content at permanent wilting point and field capacity are slightly smaller. An increase in clay content decreases lodging risk because the soil becomes stronger, an increase in the visual score increases lodging risk, because the soil becomes looser and weaker. An increase in water content at permanent wilting point increases lodging risk because less rainfall is required to wet the soil from its dry strong state to its wet weak state. Whilst the variations in risk are monotonic for these three parameters, variations in soil water content at field capacity have a more complex effect, with a peak in lodging risk at a value of 0.31. This behaviour is due to the interactions between the terms containing water content at field capacity in equations (3.12) to (3.15). At this point however the artificiality of this parametric investigation should be noted - in reality all these soil properties will vary together. This will be discussed below.

Finally, the effect of varying the crop parameters is considered. Table 4.2 shows the effect of variations in ear area, centre of gravity height, dry natural frequency, shoot number per plant, stem base radius, stem wall thickness, stem failure yield stress, root plate diameter and structural rooting depth respectively. Importantly, the variation of all these plant characters within typical UK wheat crops, apart from stem wall width, has a large effect on lodging risk. The effect of variation in ear area, centre of gravity height and natural frequency on lodging risk are in the expected directions. Lodging risk increases as ear area increases, centre of gravity height increases and as natural frequency decreases. As the shoot number per plant increases the risk of root lodging increases. With regard to the stem parameters, it can be seen for this simulation that as the radius falls below about 1.2mm the risk of stem lodging increases markedly. Similarly effects were found for variations in stem failure yield stress. Again, for this simulation, as this parameter falls below 20MPa stem lodging risk increases significantly. The effect of variations in stem wall width is minor. With regard to the root parameters Table 4.2 shows that a decrease in root plate diameter and structural rooting depth increases the risk of root lodging significantly. Once again the artificiality of this parametric investigation must be emphasised, since in practice large changes for individual crop characters whilst others remain unaltered are seldom observed. This is further considered in the discussion.

4.5 DISCUSSION

In this section we will firstly discuss the overall nature of the model set out in the previous sections and its relationship to the actual process of lodging as observed in the field. An attempt will be made to compare the results of the model in a qualitative way with field experimental data. Secondly, the adequacy of the various assumptions made in the model will be considered. Finally, the implications of the results of the parametric analysis will be discussed.

Firstly then let us consider the nature of the model itself. The model was developed with a view to incorporating the major physical phenomena associated with lodging in a conceptual framework that could be easily and quickly implemented on PCs, and might ultimately prove useful in a practical situation. As such the prediction of lodging risk for a crop in any one year was seen to be of fundamental interest. However there are two implicit assumptions within the model. The first is that it assumes a constancy of crop parameters throughout the lodging season, yet it is known that these can vary significantly even during the period of highest lodging risk (Crook *et al.* 1994). The second is that it is implicit within the formulation that the lodging risk is predicted for a homogeneous area of crop during a particular lodging season. However it is known that crop and soil parameters and lodging risk can vary significantly throughout fields. For example, lodging is found most often within the headland rather than within the tramlines (Chapter 2). In addition, lodging very often seems to initiate at a vulnerable region, and surrounding plants lodge due to a 'domino' effect. Thus to properly validate the model, a very long term experiment would need to be carried out where a uniform crop is grown in uniform soil conditions over a large number of years. The proportion of years when lodging occurred would then represent the lodging probability as predicted by the model. Clearly even if it were possible to grow a uniform crop in uniform soil conditions, and to repeat this in succeeding years, such an experiment would not be possible within realistic resource limitations. The type of data that can readily be obtained however is information on the timing and proportion of crop area lodged for different crop and soil types. Thus to confirm the adequacy or otherwise of the modelling approach it would seem that there are two possible courses of action. Firstly the model could be extended to take into account spatial non-uniformity of crop and soil, and variations in these parameters through the lodging season. Whilst this would certainly be possible, and would indeed have some merit as a fundamental research tool for the investigation of the lodging phenomenon, it would significantly increase the complexity of the model in computational terms and make its repeated use difficult and computationally very expensive. The other approach, the one followed here, is to view the model results as giving an indication of the susceptibility of a crop to lodging. As such its results can be compared directly with measured indicators of crop susceptibility to lodging such as percentage area lodged in a particular season.

The procedure followed to assess the adequacy of the model was as follows. Firstly the data from the experiments reported in (Chapter 5) comparing the effect of different agronomic treatments on the parameters that affect lodging risk, and lodging itself, was analysed. For each experimental plot a graph of percentage lodged area against time was produced and the area under the curve found. This gives some indication of the susceptibility of the crop to lodging - significant early season lodging will occur for the susceptible plots, and thus the area under the lodging curve will be high, whilst for those less susceptible plots only late season lodging will occur with a smaller proportion of area lodged, and thus the area under the lodging curve will be small. The data for the individual plots was then ranked, i.e. the plot with the smallest area under the lodging curve was given a value of one, the next a value of two and so on. The model was then run for the soil and crop parameters measured in July for each plot, and lodging risks calculated. The plots were then given a rank in terms of predicted lodging risk in a similar way. Some plots were predicted to have identical lodging risks and these plots were given equal ranks. The two sets of rankings were then plotted against each other, as shown in Figure 4.8. The results are encouraging. There were 38 plots where no lodging was observed or predicted by the model (shown as one point at the origin of the graph). There were a further 21 plots where large amounts of lodging occurred which was predicted by the model, shown by the points in the upper right of the graph. In four plots lodging was predicted where none occurred (the points on the y axis of the graph) and in nine plots lodging was observed but not predicted (the points on the x axis of the graph). The model thus correctly predicted lodging in 21of the 30 lodged crops and nil lodging for 38 of the 42 standing crops, i.e. for 82% of the experimental plots the model can be seen to be predicting lodging susceptibility quite well. These results give some confidence in the applicability of the model.

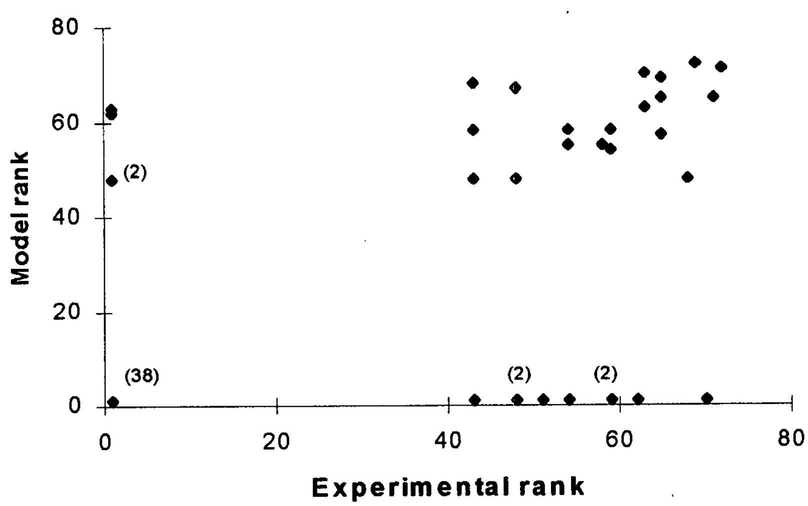


Figure 4.8 Experimental and model predicted rankings of lodging susceptibility

Now let us consider the various assumptions made in the model. Firstly consider the assumptions made about the meteorological conditions. It was assumed that the parameters of relevance to the lodging process were the daily rainfall and the maximum wind gust that could be expected to occur in any one day. The probability distributions for obtaining realisations of these parameters are reasonably well founded and reliable. However, in reality it is likely that the wind and rain probability distributions will not be independent as assumed in the model, but linked in some way. The model does not take this into account because of a lack of readily available data on linkage. An analysis of suitable met station measurements could provide the necessary information if sufficient resources were available to carry out such a study in the future. It was further assumed that the nature of the wind above a wheat canopy is such that occasional strong gusts penetrate down into the canopy, and these are the ones associated with the lodging process. In broad terms this is in agreement with published data, but a major assumption made here is that the strength of these gusts can be estimated from the wind characteristics about one metre above the top of the canopy. This assumption must be regarded as fairly arbitrary.

Now consider the nature of the dynamic model used to predict the stem base bending moment. This is based on the work of Baker (1995) and its application to isolated and forest trees suggests it is a reasonable approximation to reality. Effectively it assumes a two mass system - one mass representing the ear, and the other representing the root ball, connected by a weightless elastic stem, and is relatively simple to implement. It suggests that the natural frequency is a parameter of major importance in determining the stem base bending moment. The major weakness of this aspect of the model is the rather arbitrary correction of natural frequency to allow for root loosening effects when the soil is weakened by moisture i.e. the value k_4. More experimental data is required here.

The root component of the model is based on the work of Crook and Ennos (1993) and represents a straight forward way of relating root failure moment to root plate diameter and soil shear strength, that is dimensionally correct and theoretically reasonable. There is some uncertainty in the value of the constant of proportionality within the model (k_5), and more work is needed to determine this constant for a variety of soil types.

The soil component requires the most modification of the various aspects of the model. Whilst being set in a theoretically consistent format, its precise nature is very dependent upon experimental work carried out on only one soil type, and it is only strictly applicable to soils with a clay content greater than 0.15g/g. More experimental information for different soil types might help to better define this aspect of the model, although determination of soil strength for surface layers of different agricultural soil types is not trivial.

In the implementation of the model a number of parameter values are assumed (see the fixed parameter list of Table 1). The results from the model suggest that whilst the predicted lodging risks are not particularly sensitive to some of these parameters (turbulence length scale, damping ratio, observation time) it is reasonably sensitive to others (turbulence intensity, drag coefficient). Again more experimental data is needed to better define the range of values for these parameters.

The model assumptions having been considered, let us now consider the implications of the results of the parametric analysis of the last section. From the results of the parametric analysis shown in Table 2 and Figures 3 to 5 the following main points emerge.

a) The occurrence of root, stem or combined root and stem lodging depends upon the relative magnitudes of a number of variables - it is overly simplistic to state that lodging is due to one or other of the mechanisms, since, given suitable circumstances both may occur. Nonetheless root lodging was the most frequently predicted form of lodging, as has been found by previous authors (Pinthus, 1973, Graham, 1983, Easson *et al.*, 1993)

b) Variation in UK wheat crop characteristics influence lodging risk as much, or more, than the weather at the time of lodging. The state of a wheat crop can be manipulated by different cropping practices, thus indicating that lodging risk may be effectively controlled despite the unpredictable influence of weather.

c) It should be noted that soil water content at field capacity and permanent wilting point are strongly influenced by clay content and soil structure. For example, a soil with a high clay content is inherently strong and would be expected to decrease root lodging risk. However, this type of soil also has a high water content at field capacity (Rowell, 1994) which will reduce its strength in the wet state. This study indicates that wheat crops grown on soils containing a large proportion of clay are less lodging prone than crops grown on lighter soils. However, more precise information about the relationship between the clay and water contents of different soils is required to provide firm conclusions about this. The relationship between soil characteristics and lodging risk is further complicated by the effects of soil on the aerial components of the crop. Crops on light soils are more prone to water and nutrient deficiencies, with the consequent reductions in above ground growth. This is likely to manifest itself in, for example, fewer shoots per plant, shorter stems (lower centre of gravity) and possibly reduced ear area. All of these characters will result in a smaller base bending moment being exerted on the root/soil system and smaller lodging risk.

d) The importance of variation in certain crop characters on lodging risk is apparent. However, the results of the parametric analysis for the effects of individual crop characters on lodging risk must be treated with caution because only occasionally will individual characters change whilst others remain unaltered e.g. two varieties have been observed to have a similar base bending moment and stem failure moment, whilst differing only in root plate diameter (Chapter 6). More commonly, crop characters do not vary independently. It will be observed in Chapter 6 that reduction of seed rate caused an increased shoot number per plant but a proportionally greater increase in root plate diameter and root failure moment. Therefore, in this case an increase in shoot number was associated with a reduction in root lodging risk. Strong positive correlations have been observed for root plate diameter with structural rooting depth and stem base radius with stem wall width. Height at centre of gravity has been negatively correlated with natural frequency. It is probable that other correlations which are more complex also exist. In order to carry out a more realistic parametric analysis, related plant characters need to be identified and varied together. This may be carried out most effectively by investigating the effects of husbandry practice on the lodging associated plant characters and lodging risk.

4.5.1 Concluding remarks

From the preceding sections it can be seen that the lodging model as developed is a useful tool to help understand the lodging process, and its predictions for crop susceptibility to lodging are in broad agreement with lodging experienced in field experiments. The model has proved to be particularly useful for the identification of crop and soil parameters that are of most significance to the lodging process. These include soil clay content, soil visual score, root plate diameter, shoot number per plant, natural frequency, stem radius and stem failure yield stress. This suggests that to reduce lodging risk energies should be directed towards making modifications to these parameters wherever possible.

However the model has certain limitations, some of them severe. There are a number of parameters that have not been fully considered - in particular ear drag coefficient, turbulence intensity and the coefficients of proportionality k_4 and k_5. Also the nature of wind gust above crop canopies is not well specified, and the various formulae used to calculate soil strength are to a large extent based on empirical data. More fundamental experimental work is required in these areas to optimise the model.

The model itself could also be usefully extended to take account of spatial non-uniformity in the crop and variations in the crop parameters through the lodging season. Whilst such a model would be necessarily complex and computationally expensive, it would nonetheless be an extremely useful research tool to further help in understanding and controlling the lodging process.

The weather, soil and plant factors identified in this chapter as being influential in lodging have been measured in the experiments of the lodging project, which are described in Chapter 5. Chapter 6 uses the lodging model as an aid to understand the mechanisms by which husbandry decisions affect lodging risk. Finally, Chapter 7 attempts to predict the summer-time values of the most important lodging associated plant characters, identified here, using spring crop measurements and field observations.

5. FIELD EXPERIMENTS 1993-94, 1994-95 & 1995-96

5.1 OBJECTIVES

To define those crops for which some change in management is likely to be cost effective for lodging control.

5.1.1 Detailed objectives

To establish an array of treatments at ADAS Rosemaund that encompassed the elements of crop husbandry that are known to be critical in determining lodging risk.

To compare methods of lodging control against untreated plots using treatments thought most likely to lessen lodging.

To monitor the timing and form of lodging.

To provide estimates of centre of gravity height, natural frequency, stem strength and anchorage strength necessary to develop a model to assess lodging risk.

To measure a range of possible predictors of lodging risk in spring.

5.2 METHODS

5.2.1 Timetable

The experiment lasted for three years commencing in September 1993 and finishing in September 1996.

5.2.2 Experimental site

The experimental work was conducted at ADAS Rosemaund Research Centre, Preston Wynne, Hereford. ADAS Rosemaund was chosen as the site at which to conduct the experiment for specific reasons. Firstly, Rosemaund has silty clay loam soils, retentive of nutrients and moisture, which promote high yielding crops with large leaf canopies. Secondly, Rosemaund is situated in the West of the country, which has a higher average rainfall than the East. Both these factors were expected to increase the chances of lodging occurring during the experimental programme.

5.2.3 Treatments

a) Time of Sowing

i. mid-late September, or as soon as possible thereafter
ii. mid-late October, but at least 3 weeks after the first sowing

b) Seed rate

i. 500 seeds m^{-2} (high)
ii. 250 seeds m^{-2} (low)

c) Residual Nitrogen

i. 1993-94:- 80 kg/ha N in autumn, before sowing
1994-95:- 330 kg/ha N on previous crop (spring oilseed rape)
1995-96:- 350 kg/ha N on previous crop (spring oilseed rape)

ii. 1993-94:- Nil
1994-95:-30 kg/ha N on previous crop
1995-96:-50 kg/ha N on previous crop

d) Lodging control methods

i. Nil
ii. 2.5 l/ha chlormequat + choline chloride @ GS 31 (New 5C Cycocel)
iii. as ii, plus 2-chloroethylphosponic acid + mepiquat chloride @ GS 45 (Terpal) at 1.5 l/ha.
iv. "Canopy Management" (method as described in Link N Report).

5.2.4 Experimental Design and Analysis

The main experiment was a split split plot design with time of sowing treatments on main plots, seed rate treatments on sub-plots and residual nitrogen and lodging control treatments randomised on sub-sub-plots. Individual sub-sub-plot sizes were 4m x 18m. Three replicates giving 96 plots.

5.2.5 Procedures

Certified winter wheat seed cv. Mercia
Nitrogen applied as ammonium nitrate (Nitram)

5.2.5.1 Site management

Seedbeds

The whole site was ploughed prior to the first time of sowing. The area for the first time of sowing was worked down with a power harrow or similar to produce a fine tilth. The seedbed for the second time of sowing was worked down prior to drilling.

Seed rate

The drill was calibrated for high and low seed rates, with discards drilled in low seed rate.

Crop protection

A prophylactic programme of disease, weed and pest control was used for all the experiments. Treatments were therefore dependent upon the diseases, weeds and pests encountered locally (HGCA Development contract R & D protocol, 1994). See Appendix 2 for site records.

Nitrogen

All N was spread by hand.

See Appendix 2 for site records and nitrogen and PGR applications

5.3 PLANT MEASUREMENTS

5.3.1 Plant sampling

Plant population counts were carried out soon after full emergence. Plants were counted in the row either side of a 0.5m bar placed between the rows. Three such counts were made in each plot.

Two methods of plant sampling were used; $0.72m^2$ (1.2 m x 0.6 m) quadrat samples for growth analysis and a sample of ten plants (including structural roots), for detailed lodging specific measurements. See Table 5.1 for assessment dates.

Table 5.1 Assessment dates

Growth stage	1993-94 TOS 1	1993-94 TOS 2	1994-95 TOS 1	1994-95 TOS 2	1995-96 TOS 1	1995-96 TOS 2
30	11Apr	20-Apr	23-Feb	03-Apr	18-Mar	22-Apr
31	02-May	10-May	22-Mar	10-Apr	02-Apr	29-Apr
33	-	-	27-Apr	3-May	26-Apr	14-May
39	20-May	30-May	12-May	18-May	24-May	31-May
59	-	-	05-Jun	05-Jun	11-Jun	14-Jun
69	-	-	26-Jun	26-Jun	-	-
72	08-Jul	14-Jul	03-Jul	03-Jul	01-Jul	02-Jul
85	05-Aug	09-Aug	-	-	2-Aug	2-Aug

The protocol for determining quadrat sample areas is given in the Sylvester-Bradley et al., (1998b). Each quadrat was oriented so that one row of plants passed through diagonal corners of the quadrat. For the 1993-94 trial, plants were dug up with their roots at all growth stages. For the 1994-95 and 1995-96 trials, plants were dug up at GS 30 and 31 only. At later growth stages the above ground material was cut off at ground level in the field. The objective was to recover all above ground plant material. Once sampled, the plant material was stored at 4°C until analysis.

Ten plants were selected randomly from around the edge of the quadrat area. Two plants were dug from each of the two short quadrat sides and three plants dug from each of the two long quadrat sides, to give a total of ten plants. Care was taken during plant extraction to ensure that the structural crown roots were completely recovered. The plants were then placed in plastic bags and stored at 4°C, until analysis.

5.3.2 Growth analysis

Growth analysis was carried out on plant material collected from the quadrat sampling. For all samples taken at or before GS 31, soil was cleaned off the roots and the plant number of the whole sample recorded. For all samples in the 1993-94 trial the roots were cut off and their fresh weight (g) recorded. Then a 15% sub-sample (SS1) of roots were randomly selected, their fresh weight taken and dry weight (g) determined after oven drying at 80°C for 48 hours.

Growth analysis of the above ground plant material was identical for samples taken at all growth stages. Above ground fresh weight, dry weight and green area of the leaves, stems and ears together with the number of fertile, dying and dead shoots were determined on the basis of a 12% subsample (HGCA 1998). See Table 5.2 for details of the growth analysis measurements taken in the field trials.

Table 5.2 Growth analysis measurements

	1993-94	1994-95	1995-96
Plant number m^{-2}	✓	✓	✓
Root dry and fresh weight (t ha^{-1})	✓		
Shoot (fertile & dying+dead) /ear number m^{-2}	✓	✓	✓
Leaf dry and fresh weight (t ha^{-1})	✓	✓	✓
Leaf area index	✓	✓	✓
Stem dry and fresh weight (t ha^{-1})	✓	✓	✓
Stem area index	✓	✓	✓
Ear dry and fresh weight (t ha^{-1})	✓	✓	✓
Ear area index	✓	✓	✓

5.3.2.1 Harvest analysis

Pre-harvest analysis

Just prior to harvest ear number m^{-2} was determined using one of two methods. In the 1993-94 and 1994-95 trials the number of ears within a quadrat measuring 0.5m x 0.5m were counted. This was repeated five times in each plot and the mean taken. In the 1995-96 trial the number of stems (with ears) were counted on either side of a 0.5m bar placed between the rows. Ear number m^{-2} for a plot was then calculated using the mean of five such samples and the row width.

Grab samples of approximately 100 stems with ears were taken from five randomly chosen areas in all plots by cutting the stems at ground level. These were processed in the laboratory to determine dry matter harvest index and ear and straw fresh weight. Fresh weight of the total sample was recorded, then all ears were cut off and counted, and straw and ear fresh weights were recorded. A random 10 to 15% sub-sample of straw was selected, weighed to determine fresh weight, then oven dried to determine dry weight. All the ears were then threshed and the grain and chaff were collected. Fresh and dry weights of grain and chaff were measured.

Combining of plots and harvest analysis

Prior to harvesting, tramlines were cut out, so that they did not form part of the harvested area and plot lengths were measured. For the harvest, one combine strip was taken through the centre of the combine area of the plot (to avoid plants influenced by the 'edge effect'). The width of the combine strip was accurately recorded; the area taken was approximately 10m x 2.25m. All fresh grain from each plot was weighed on the combine and a 1 kg sample of grain was taken for measurements of thousand grain weight, specific weight, Hagberg falling number and grain moisture content. Plot yields were expressed as tonnes per hectare (t ha^{-1}) at 85% dry matter.

5.3.3 Lodging specific measurements

Lodging specific measurements were recorded on the ten plant samples. Details of the lodging specific measurements made are given in Table 5.3.

Table 5.3 Lodging specific measurements

	1993-94	1994-95	1995-96
Leverage measurements			
Stem height (m)	✓	✓	✓
Centre of gravity height (m)	✓	✓	✓
Natural frequency (Hz)	✓	✓	✓
Plant fresh weight (g)	✓	✓	✓
Ear fresh weight (g)	✓	✓	✓
Ear area (cm^2)	✓	✓	✓
Shoot number per plant	✓	✓	✓
Stem strength measurements			
Internode length (mm)	✓	✓	✓
Internode diameter (mm)	✓	✓	✓
Internode wall width (mm)	✓	✓	✓
Internode fresh and dry weight (g)	✓	✓	✓
Internode breaking strength (g)	✓	✓	✓
Anchorage strength measurements			
Crown depth (mm)	✓	✓	✓
Crown width (mm)	✓	✓	
Plant width at soil surface (mm)	✓	✓	
Crown root number per plant	✓	✓	✓
Root plate spread (mm)	✓	✓	✓
Rigid root length (mm)	✓		✓
Angle of root spread	✓	✓	
Anchorage failure moment (Nm)	✓	✓	✓

5.3.3.1 Stem base component measurements

All stem base component measurements were done in the laboratory. For the purpose of this section the stem base consists of the basal internode, internode 1 and internode 2 only. Stem internodes were numbered according to the following methodology which remains consistent throughout the report; an internode which originated at or just below the ground surface and was more than 10 mm in length was numbered as internode 1. Subsequent internodes up the stem were then numbered 2, 3, 4, 5 etc., with the final uppermost internode referred to as the peduncle. Basal internodes were defined as those which were 10 mm or less in length and were generally situated at or just below ground level, always preceding internode 1 (Kirby *et al.*, 1994).

Main stems of each ten plant sample were identified using the method described in Kirby and Appleyard (1984), and their leaves removed. Measurements for the determination of stem failure moment and its components were then carried out on the basal internode, internode 1 and internode 2 of each main stem.

The length of each internode (mm) was measured from the mid-point of its adjacent nodes. Stem diameter (mm) was measured at the middle of each internode, using digital callipers (Etalon). Tensile stem failure strength (g) was measured using a three-point bending test (Graham, 1983; Easson, White & Pickles, 1992). A vice was used to support the stem by adjusting the vice jaws to the exact length of each internode. The adjacent nodes of the internode were placed over the vice jaws and a pulling pressure was applied to the middle of the internode using a graduated Salter spring balance (1kg x 10g or 5kg x 25g). The hook of the spring balance was placed around the middle of the internode and pulled at an even rate until the stem buckled, at which point the force applied was recorded. Internodes were then cut at their centre point and digital callipers were used to measure the stem wall width (mm). For the 1995-96 experiment two measurements of stem wall width were taken on opposite sides of the stem, from which a mean was taken. Finally, stem failure yield stress (Nm) was then calculated from the internode diameter, wall width and failure moment using basic structural theory for a thick walled cylinder (Baker, 1995).

5.3.3.2 *Aerial component measurements*

Laboratory measurements
To find the height at centre of gravity of the main shoot, the roots were cut off and the main shoot was balanced on a ruler (leaves and ear still attached) (Crook and Ennos, 1994). The distance from the point of balance to the stem base, was then defined as the height at centre of gravity (m) of the main stem. Height at centre of gravity was also measured for whole plants in the 1994-95 experiment. The same method was used, except that the roots were trimmed so as not to separate the shoots at the stem base, enabling all the shoots to be balanced together.

The area (cm^2) of ten main stem ears was measured using an image analyser (Delta-T Devices). Crop height (m) was measured from the soil surface to the topmost leaf ligule or base of the ear collar (when emerged). Shoot number per plant was recorded as was the number of internodes on each main stem. In the 1994-95 experiment ear fresh weight (g) was measured, using digital scales (Mettler).

In-field measurements

Natural frequency was measured by plant oscillation tests in the field. Firstly the main stem was identified and the surrounding stems were held away using a plastic cone placed over the main stem (narrow end first). The main stem was then pulled back (at the ear collar) 10 cm from the vertical, and released. After release the number of 'significant' oscillations of the stem were counted and timed using a stopwatch. 'Significant' oscillations were defined as those where the stem oscillated straight back and forth in the same line as it was released. If the stem adopted circular oscillations i.e. oscillated laterally, the test was repeated. Natural frequency was calculated as the average time for one complete oscillation.

5.3.3.3 *Root anchorage component measurements*

Laboratory measurements

Seed depth (mm) was recorded at GS 30, by measuring from the seed case to the soil surface, defined as the junction between white and green tissue. In the 1994-95 experiment the presence or absence of a sub-crown internode between the seed and crown was also recorded.

The plant crown was defined as the origin of all tillers and adventitious roots (except the coleoptile tiller and its associated roots, should a sub-crown internode exist). Crown depth (mm) was measured from the base of the crown to the soil surface. In the 1993-94 and 1994-95 experiments the width of the crown base (mm) was also measured.

The width of the plant base at the soil surface was measured in millimetres. The stems of the plant were held in a similar position to that observed in the field for this measurement. The position on the stems at soil surface was identified by a change in stem colour from white to green, or by the point at which soil no longer adhered to the stems.

The number of crown roots were counted on each plant. Crown roots were identified by their inherent rigidity and tendency for soil particles to stick to them due to their dense covering of root hairs (rhizosheath). This distinguished them from seminal roots, which emerged from the seed, numbered six or less, were much less rigid and usually had no soil adhered to them (Ennos, 1991).

Crook and Ennos (1993) have described how the pattern of crown root development forms a 'root cone' (Figure 5.1), whose base is defined as the point along the crown root at which it is no longer sufficiently rigid (stiff) to provide anchorage. This section of crown root was identified by the point at which the root became more flexible, thinner and no longer had a dense covering of hairs on which soil was adhered. Root plate spread was defined as the width of the 'root cone' base (Figure 5.1). Both the maximum root plate spread (mm) and the root plate spread orientated at right angles to the maximum were measured. The second measurement was often the minimum root plate spread. These two measurements was then averaged to gain the mean root plate spread. In the 1994-95 experiment the angle of root spread was also measured (Figure 5.1). As with root plate spread, a maximum and minimum angle were measured at 90° to each other. In the 1995-96 experiment the length of rigid root (mm) was measured (Figure 5.1). This measurement could be described as the length of the sloping side of the 'root cone'. The method by which the length of the rigid root was identified is given in the definition of the 'root cone' base. Once again two measurements were taken, similar to those described for root plate spread and angle of root spread.

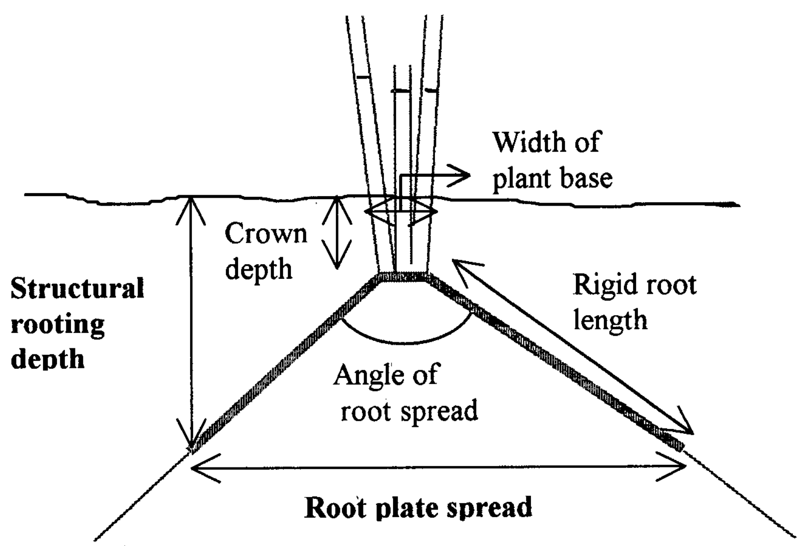


Figure 5.1 Anchorage system of a wheat plant

5.3.3.4 In-field measurements

Anchorage failure moment (Nm) was measured by plant displacement tests, using an overturning device, based on a torquemeter, designed by Ennos and Crook in 1994 (University of Manchester). The hand-held overturning device, was purpose built for use in the field, the measurement of force being based on a digital torquemeter (Mecmesin Ltd). The other appliances required for the device included; a tool chuck unit with a plastic cylinder housing, a rotation lever and displacement angle scale, ground spikes or metal base plate (for securing the device to the ground) and a rotation arm made of lightweight alloy. The method developed for measuring root anchorage resistance was modified from the method of Crook and Ennos (1994) as follows;

1. Select one plant and cut off all shoots at a height of 50 mm from the ground.
2. Position the torquemeter, so the rotation arm rests against the cut stems.
3. Rotate the arm steadily, to 45° and measure the maximum force (Nm) during the rotation.

5.3.4 Lodging and leaning assessment

When lodging was observed assessments of its severity were made using the following indices:
Index 1 % crop area upright (crop leaning between 0° and 5° from the vertical).
Index 2 % crop area leaning (crop leaning between 5° and 45° from the vertical).
Index 3 % crop area lodged (crop lodged between 45° and 90° from the vertical).
Index 4 % crop area lodged flat.
Index 5 % crop area brackled (buckling of straw 1/4 or more up its length).

During lodging assessments, the dominant mechanism and point of failure was identified and noted i.e. whether by stem failure or anchorage failure. Lodging assessments were made on areas of the plot which had not been previously sampled. A visual assessment of the percentage area of crop which was standing, leaning, lodged or lodged flat was made of the whole plot, including its edges, by walking around the plot perimeter.

5.3.5 Disease assessment

Visual assessments for common symptoms of Eyespot (*Pseudocercosporella herpotrichoides*), Sharp eyespot (Rhizoctonia cerealis), Fusarium foot rot (*Fusarium*), and take-all (*Gaumannomyces graminis*) were carried out routinely whenever other measurements were taken. For the 1994-95 experiment these diseases were present at high levels so an assessment of stem based diseases was carried out at GS 87 on all treatments. These diseases were present only at very low levels in the other experiments, so full disease assessments were not carried out.

5.3.6 Environmental measurements

Rainfall (mm) and wind speed (m s^{-1}) were measured by an 'on site' automatic portable weather station (Delta-T Devices). During the lodging risk period of June to harvest, rainfall was recorded every 10 minutes, using a tipping bucket rain gauge, attached to the weather station. Wind speed was recorded every five seconds using a high resolution anemometer. Average wind speeds were calculated from these frequent readings, using software (Delta-T View). During the rest of the growing season, rainfall, wind speed, wind direction, temperature and humidity were recorded as daily means from data sampled at 10 minute intervals. Daily sun hours and total daily radiation (kw m^{-2}) were measured a maximum of one kilometre from the field site, at the main ADAS Rosemaund weather station.

5.3.7 **Soil measurements**

5.3.7.1 Mineral N analysis

Soil cores were taken in February at 3 different soil horizons (0-30 cm, 30-60 cm, 60-90 cm) for mineral N analysis. Six cores were taken per area sampled and the three horizons for the six cores were bulked and placed in sealed plastic bags. The bulked samples were stored frozen and sent to ADAS Wolverhampton for analysis.

5.3.7.2 Topsoil nutrient analysis

For topsoil nutrient analysis, 0-15 cm soil samples at 5 points in each sample area were taken after the previous crop had been harvested. These were analysed for pH, P, K, Mg and % OM at ADAS Wolverhampton.

5.3.7.3 Soil shear strength

The following soil measurements were taken as near to the roots as possible without damaging the root structure. These measurements were taken in conjunction with natural frequency measurements, root anchorage resistance measurements and lodging events. Soil shear strength (kPa) was measured using a shear vane with a 19mm blade diameter, at 25 mm and 50 mm depths below the soil surface. The shear vane was pushed into the soil to the required depth and the torque recorder rotated at a constant speed until the soil sheared. The torque required to shear the soil was then recorded (ADAS, 1982). Ten measurements of shear strength were taken at each depth, in each plot.

5.3.7.4 Soil moisture content

After each strength reading the soil adhering to the shear vane blades was collected and stored in sealed bags for soil moisture content (g g^{-1}) determination. Stones were removed by sieving before fresh weight determination. Soil was then oven dried at 100°C for 16 hours or until it reached constant weight and its dry weight recorded.

Soil moisture content was also measured using Time Domain Reflectometry (TDR), see (Nielsen, Lagae & Anderson, 1995). TDR measures the soil moisture profile by detecting how changes in soil moisture content influence the waveform of electrical pulses emitted and reflected within a soil profile,, from the TDR. TDR had the advantage over the gravimetric method of providing continuous data which could be downloaded regularly from a logger in the field. The TDR had 16 probes which could be positioned at different depths or positions in the soil, to determine rates of wetting and drying of the soil during periods of high lodging risk. The TDR was installed on 21-Jun-94 and 26-Jun-95 in the main trials at ADAS Rosemaund. 4 plots were monitored by the TDR probes (4 probes per plot, spaced at even distances along the plot length) from the end of June to early August. The probes (about 150 mm in length) measured soil moisture at intervals along their length, with the actual soil moisture value being an average of these readings. The probes were inserted into the soil diagonally, to record soil moisture in the 0-10 cm horizon.

5.3.8 Other measurements

Video recording of the crop was carried out over the lodging period, using a Sony high-resolution camcorder, with a time lapse device, weather-proof housing and tripod. When windy or wet weather conditions were forecast, the camera was set up in a high lodging risk plot to record crop movement with the aim of recording lodging events.

5.4 RESULTS & DISCUSSION

5.4.1 Weather

During the 1993-94 growing season rainfall (Figure 5.2) was well above average over autumn (which delayed drilling) and winter 1993-94. Air temperatures (Figure 5.3) and sunshine hours (Figure 5.4) were generally below average for this period. During late spring and summer 1994 (with the exception of May) rainfall was well below average, with dry weather in June and especially in July. Less than 50 mm fell during June and July compared to the 30 year long term mean (LTM) of 98 mm for both months. Average daily wind speeds (Figure 5.5) were about 1.5 m/s in July, just below average, whilst sunshine hours and air temperatures were both above average during the summer months.

The 94-95 growing season was characterised by a very warm November and winter months followed by average or slightly above average temperatures until harvest. Sun hours were similar to the long term mean apart from a very dull November and above average sun hours in March and April. September had twice its average rainfall and was followed by a wetter than average winter. Spring rainfall was below average with April receiving less than 50 % of its normal rainfall. June and July were very dry, with 12 mm and 6 mm rain compared with long term averages of 50 mm and 48 mm respectively. Wind speeds were average or slightly below average for the summer months.

The 95-96 season had a warmer than average October followed by a colder than average winter. The rest of the growing season had temperatures similar to the long term mean, apart from May which was slightly colder. Average sun hours were experienced for the autumn and winter, followed by a very dull March which experienced less than half of its long term mean sun hours. The remainder of the growing season had sun hours similar to the long term mean, with June and July slightly above average. Average amounts of rain fell in autumn and winter followed by slightly above average rain in March and April. May to July had below average rain, with June receiving less than 50 % of its long term mean. August rainfall was however average. Mean wind speeds were slightly below average in June and July, but average in August.

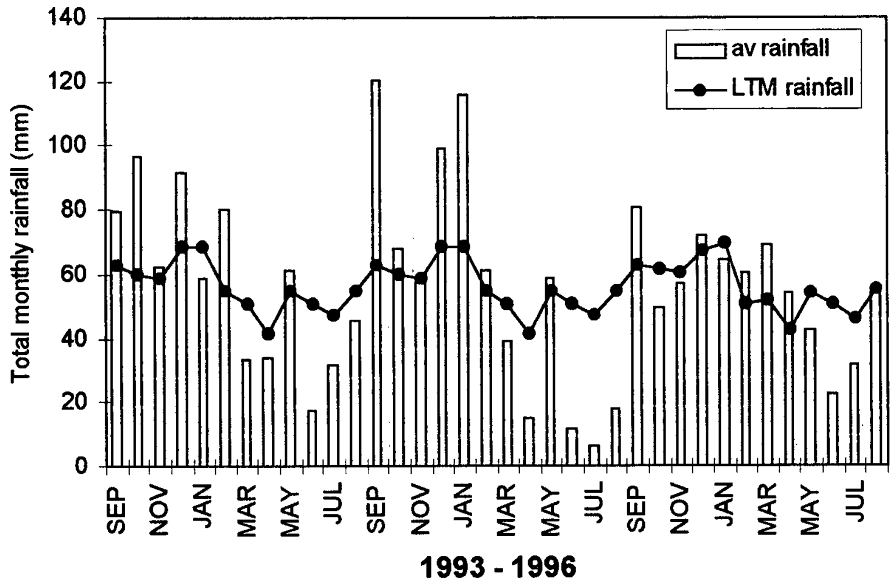


Figure 5.2 Total monthly rainfall at ADAS Rosemaund (1993-96) compared with the 30 year long term mean (LTM).

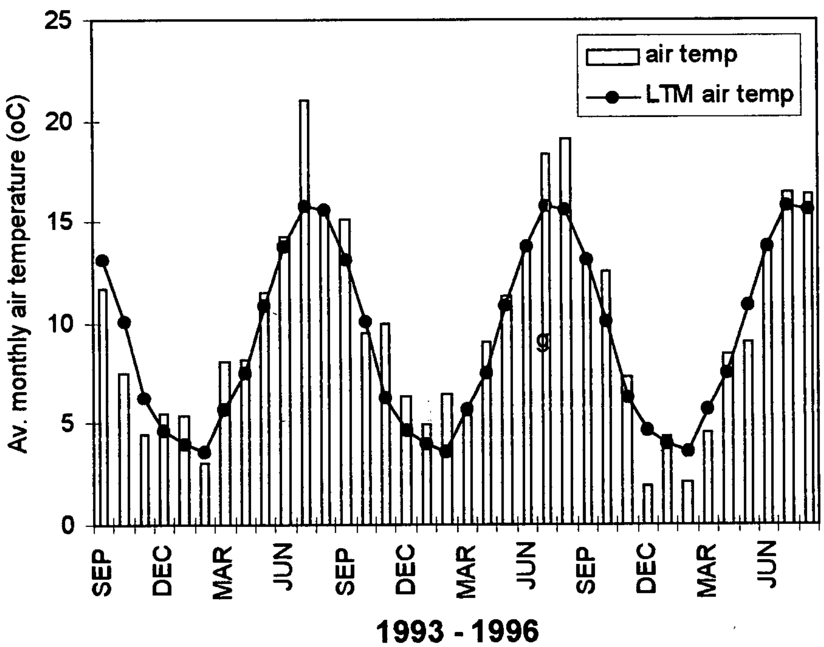


Figure 5.3 Average monthly air temperature at ADAS Rosemaund (1993-96) compared with the 30 year long term mean (LTM).

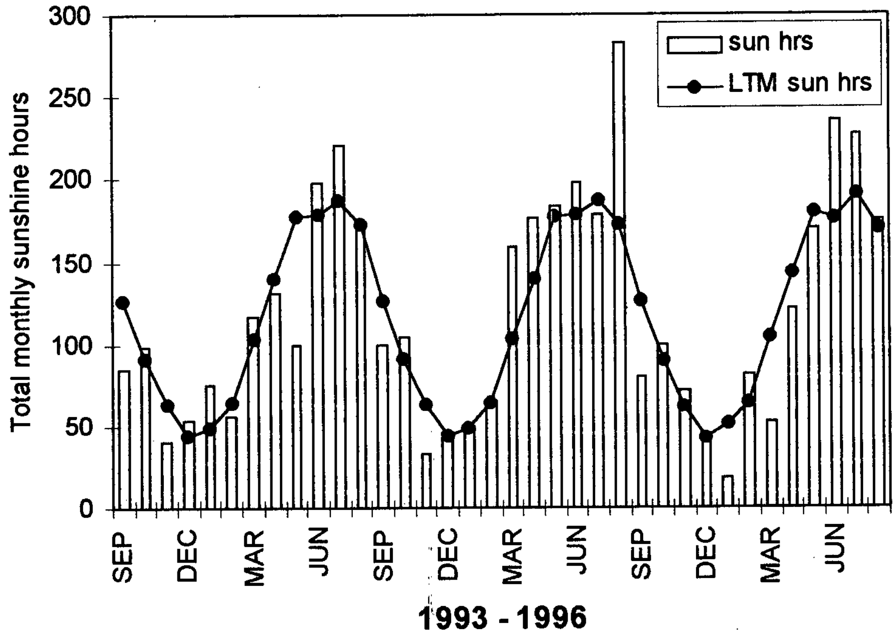


Figure 5.4 Total monthly sunshine hours at ADAS Rosemaund (1993-96) compared with the 30 year long term mean (LTM).

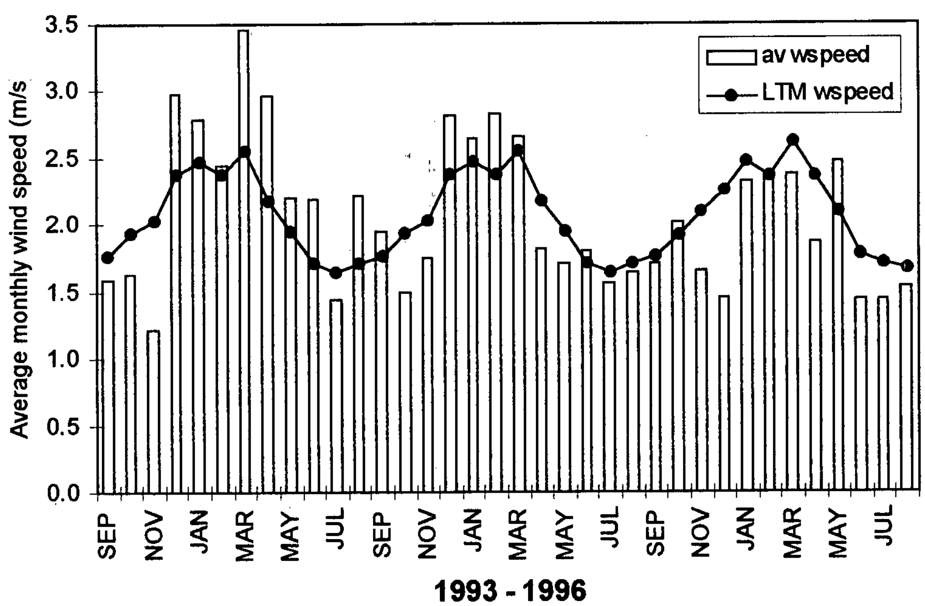


Figure 5.5 Average monthly wind speed at ADAS Rosemaund (1993-96) compared with the 30 year long term mean (LTM).

5.4.2 Sowing dates

Sowing dates for the three experiments are shown in Table 5.4. Sowing dates were always greater than three weeks apart. However, drilling was later than desired in the 93-94 experiment due to wet weather.

Table 5.4 sowing dates

Treatment	1993-94	1994-95	1995-96
Early sowing	16 October	23 September	20 September
Late sowing	8 November	17 October	1 November

5.4.3 Plant establishment

Establishment in the 1993-94 experiment (Table 5.5) was poor due to very dry soil conditions resulting in a cloddy seed bed. This resulted in a moderate to low plant population for the high seed rate treatment and a very low plant population for the low seed rate treatment.

Table 5.5 Plant establishment for the 1993-94 experiment.

time of sowing	seed rate / m^2	plant number / m^2	**% establishment**
16-Oct-93	500	197	39
16-Oct-93	250	60	24
08-Nov-93	500	225	45
08-Nov-93	250	140	56

NB 50% Emergence Dates : early sowing date (18-Nov), late sowing date (14-Dec).

In 1994-95, better drilling conditions and a good seedbed led to good establishment at both sowing dates and seed rates, creating contrasting plant densities, as intended (Table 5.6).

Table 5.6 Plant establishment for the 1994-95 experiment.

time of sowing	seed rate / m^2	plant number / m^2	**% establishment**
23-Sep-94	500	470	94
23-Sep-94	250	233	93
19-Oct-94	500	400	80
19-Oct-94	250	210	84

50% Emergence Dates : early sowing date (06-Oct), late sowing date (04-Nov)

In the 1995-96 experiment, both early sown, high and low seed rate crops established well (Table 5.7). The late sown crops had poorer establishment, resulting in lower plant populations in spring, probably as a result of cold temperatures in late-November and December.

Table 5.7 Plant establishment for the 1995-96 experiment.

time of sowing	seed rate / m^2	plant number / m^2	**% establishment**
20-Sep-95	500	467	93
20-Sep-95	250	199	80
01-Nov-95	500	326	65
01-Nov-95	250	158	63

50% Emergence Dates : early sowing date (27th Sept), late sowing date (20-Nov)

5.4.4 Spring soil mineral nitrogen

In all experiments, the high residual nitrogen treatment had a significantly greater soil mineral nitrogen level, measured in February, than the low residual nitrogen treatment, ($P<0.01$). In the 1993-94 experiment the high and low residual nitrogen treatments averaged 101 and 72 kg ha $^{-1}$ N respectively across treatments. In the 1994-95 experiment the high and low residual nitrogen treatments averaged 85 and 46 kg ha $^{-1}$ N respectively across treatments, for a 90 cm deep soil profile (Table 5.8). In the 1995-96 experiment the high residual nitrogen and low residual nitrogen treatments averaged 116 and 71 kg ha $^{-1}$ N respectively for a 90 cm deep soil profile (Table 5.9).

Table 5.8 Spring soil mineral nitrogen (kg ha^{-1} N) for the 1994-95 experiment.

	23 September sowing		**19 October sowing**		
	500 seeds m^{-2}	**250 seeds m^{-2}**	**500 seeds m^{-2}**	**250 seeds m^{-2}**	Average
High soil residual N	78	79	87	96	**85**
Low soil residual N	41	38	47	59	**46**

SED = 16.1 (23 df)

Table 5.9 Spring soil mineral nitrogen (kg ha^{-1} N) for the 1995-96 experiment.

	20 September sowing		**1 November sowing**		
	500 seeds m^{-2}	**250 seeds m^{-2}**	**500 seeds m^{-2}**	**250 seeds m^{-2}**	Average
High soil residual N	94	111	130	132	**116**
Low soil residual N	65	65	77	77	**71**

SED = 22.0 (23 df)

5.4.5 Crop growth

A description of the growth and development of above ground dry matter, shoot number and green area index is given, using the treatments with the highest and lowest lodging risks. This was done to demonstrate the diversity of crops which could be produced by different husbandry. This section is followed by an investigation of the effects of individual husbandry treatments on crop growth, grain yield and lodging.

5.4.5.1 The 1993-94 season

Growth and development of the high and low lodging risk treatments
Due to poor plant establishment and inconsistent differences in soil residual nitrogen two treatments with different sowing dates were expected to give the greatest contrast in lodging risk in the 1993-94 experiment. The early sown, high seed rate, high residual nitrogen (1HN1) was compared with the late sown, high seed rate, high residual nitrogen (2HN1) for above ground dry weight, shoot number and green area index (Figure 5.6).

During spring the high risk crop had a slightly greater shoot density and green area index than the low risk crop. However, for the remainder of the growing season growth of the two crops was very similar. Both the early and late sown crops accumulated more than 18 t ha^{-1} dry matter by harvest. The 1HN1 and 2HN1 treatments yielded 10.4 t ha^{-1} and 11.1 t ha^{-1} (Table 5.10) respectively and had a similar percentage area lodged (Table 5.11; 10-13%).

Due to the late sowing, poor plant establishment and inconsistent differences in soil residual nitrogen there were no statistically significant effects by individual treatments on crop growth through the season, grain yield or lodging.

(a)

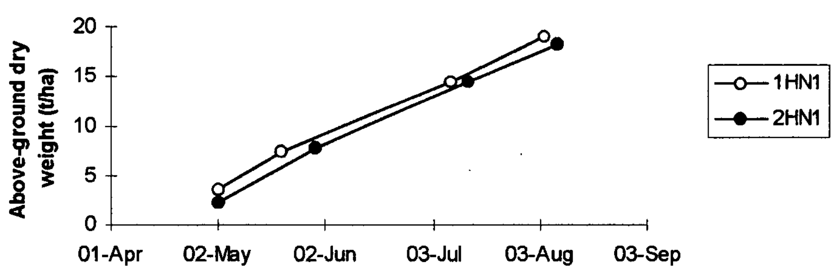


Fig 5.5a

(b)

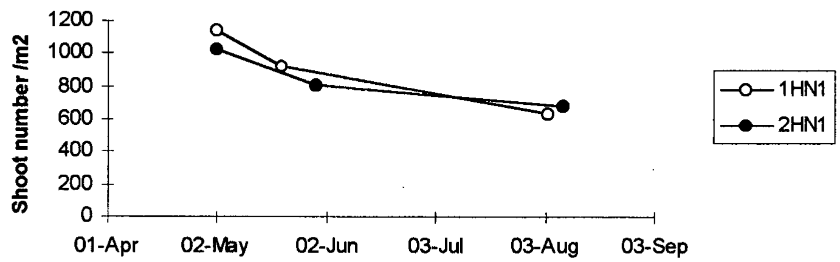


Fig 5.5c

(c)

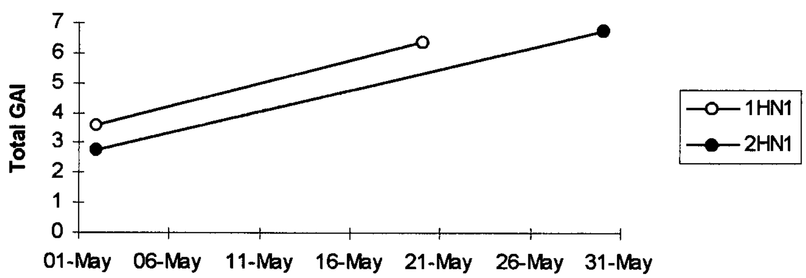


Fig 5.5d

Figure 5.6 (a) **Above-ground dry weight,** (b) **fertile shoot number and** (c) **total green area index with time for the high lodging risk (1HN1) and low lodging risk (2LO1) treatments in the 1993-94 experiment.**

Table 5.10 Grain yield (t ha^{-1}; at 85% dry matter) for the 1993-94 experiment.

Treatments		**16 October sowing**		**8 November sowing**	
		500 seeds m^{-2}	**250 seeds m^{-2}**	**500 seeds m^{-2}**	**250 seeds m^{-2}**
High soil residual nitrogen	Nil spring lodging control	10.2	10.4	10.9	11.4
	5C Cycocel (PGR)	8.1	11.2	11.9	10.9
	5C Cycocel + Terpal (PGR)	9.0	11.4	11.8	11.0
	Canopy Management	8.4	10.4	8.7	9.3
Low soil residual nitrogen	Nil spring lodging control	10.4	10.9	11.4	10.7
	5C Cycocel (PGR)	9.1	11.1	11.8	11.3
	5C Cycocel + Terpal (PGR)	10.5	10.9	11.5	11.2
	Canopy Management	8.2	9.0	10.4	9.9

SED = 0.65 (56 df)

Table 5.11 Percent area lodged at harvest in the 1993-94 trial

Sowing date	Seed rate	Soil residual N	Lodging control	**Total % area lodged**	% area leaning (5-45°)	% area (45-90°)	% area lodged flat
EARLY SOWING	HIGH SEED RATE	High soil N	Nil	**10**	5	5	0
			5C Cycocel	**2**	2	0	0
		Low soil N	Nil	**1**	0	0	0
			5C Cycocel	**0**	0	0	0
LATE SOWING	HIGH SEED RATE	High soil N	Nil	**13**	6	7	0
			5C Cycocel	**0**	0	0	0
		Low soil N	Nil	**1**	0	0	0
			5C Cycocel	**0**	0	0	0

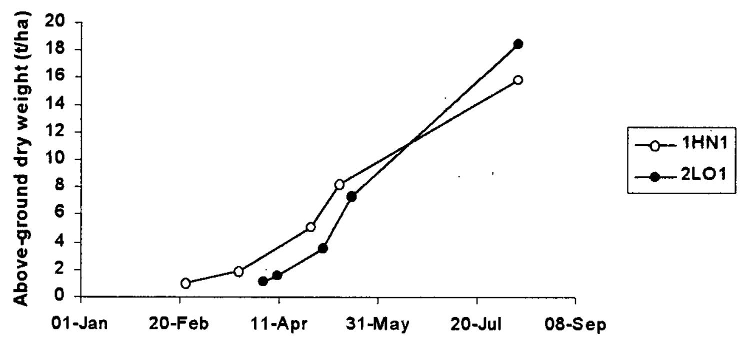
5.4.5.2 The 1994-95 season

Growth and development of the high and low lodging risk treatments

The high risk treatment; early sown, high seed rate, high residual nitrogen without PGR (1HN1) was compared with the low risk treatment; late sown, low seed rate, low residual nitrogen (2LO1) in Figure 5.7.

Development of the high risk treatment was ahead of the low risk treatment until the end of stem extension, after which developmental dates were similar. At GS 33 and 39 the high risk treatment generally had a greater above ground dry weight, shoot number and green area index than the low risk treatment. At GS 39 the high risk treatment had a green area index of 6.6 compared with 4.9. At harvest the high risk treatment had significantly more shoots, 584 compared with 497 shoots m^{-2}, but a much smaller above ground dry matter, 15.2 t ha^{-1} and 18.5 t ha^{-1} dry weight (Figure 5.7a). The high risk treatment resulted in 72 per cent area lodged at harvest compared with an absence of lodging for the low risk treatment (Table 5.13). It should be noted that all lodging was stem lodging and apart from the high risk treatment, the lodging encountered was slight and mainly occurred late in the growing season (from GS 77 onwards). The severe lodging which occurred during grain filling in the high risk treatment may have curtailed growth. This could account for its small above ground dry weight at harvest compared with the low risk treatment.

(a)



(b)

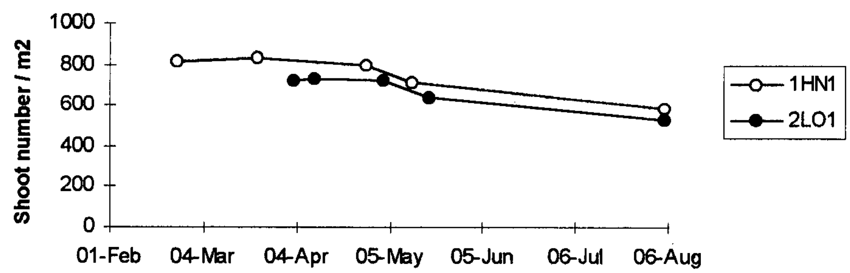


Fig. 5.7c

(c)

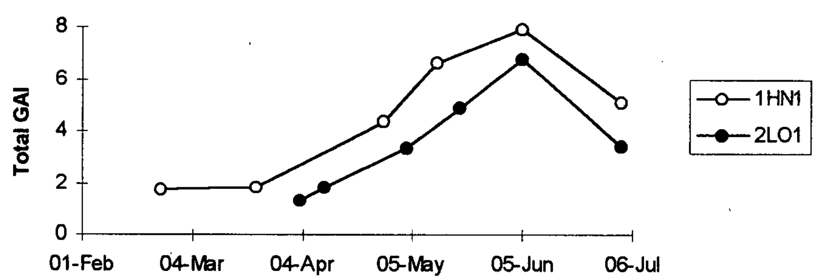


Fig. 5.7d

Figure 5.7 (a) **Above-ground dry weight,** (b) **fertile shoot number and** (c) **total green area index with time for the high lodging risk (1HN1) and low lodging risk (2LO1) treatments in the 1994-95 experiment.**

Table 5.12 Grain yield (t ha^{-1}; at 85% dry matter) for the 1994-95 experiment.

Treatments		23 September sowing		19 October sowing	
		500 seeds m^{-2}	250 seeds m^{-2}	500 seeds m^{-2}	250 seeds m^{-2}
High soil residual nitrogen	Nil spring lodging control	8.6	9.3	9.3	10.1
	5C Cycocel (PGR)	9.2	9.3	10.0	9.9
	5C Cycocel + Terpal (PGR)	9.6	10.1	10.3	10.1
	Canopy Management	9.2	9.3	10.0	9.9
Low soil residual nitrogen	Nil spring lodging control	9.6	9.6	9.9	10.0
	5C Cycocel (PGR)	9.6	9.4	9.7	9.7
	5C Cycocel + Terpal (PGR)	9.2	9.7	10.1	10.1
	Canopy Management	9.6	9.4	9.7	9.7

SED = 0.47 (56 df)

Table 5.13 Percent area lodged at harvest in the 1994-95 trial.

Sowing date	Seed rate	Soil resi-ual N	Lodging control	**Total % area lodged**	% area leaning (5-45°)	% area (45-90°)	% area lodged flat
EARLY SOWING	HIGH SEED RATE	High soil residual N	Nil	**72**	37	12	23
			5C Cycocel	**7**	5	2	0
			5C + Terpal	**5**	5	0	0
			Canopy Man.	**30**	33	7	0
		Low soil residual N	Nil	**36**	26	5	5
			5C Cycocel	**8**	6	0	2
			5C + Terpal	**7**	0	7	0
			Canopy Man.	**8**	8	0	0
	LOW SEED RATE	High soil residual N	Nil	**2**	2	0	0
			5C Cycocel	**0**	0	0	0
			5C + Terpal	**0**	0	0	0
			Canopy Man.	**2**	2	0	0
		Low soil residual N	Nil	**3**	3	0	0
			5C Cycocel	**0**	0	0	0
			5C + Terpal	**0**	0	0	0
			Canopy Man.	**0**	0	0	0

The influence of husbandry on crop growth and lodging

Sowing date

Generally no statistically significant differences were found between the two sowing date treatments throughout the growing season (GS 30 to harvest) for above ground dry weight, shoot number, green area index or for grain yield (Table 5.12). However, at GS 33 and GS 39 the high seed rate treatment which was sown early had a significantly greater green area index and above ground dry weight than the other sowing date/seed rate combinations ($P<0.05$). This may explain why the early sown treatment had significantly more lodging than the late sown treatment at harvest ($P<0.05$), with 19 out of 48 plots experiencing lodging compared with only 3 out of 48 (Table 5.13)

Seed rate

In general high seed rate had a significantly greater above ground dry weight, shoot number and green area index between GS 30 and GS 39 ($P<0.05$). These effects were often influenced by an interaction between sowing date and seed rate which was due to large seed rate differences associated with the early sowing date, but small seed rate differences associated with the late sowing date. By harvest no statistically significant differences were found due to seed rate for above ground dry weight, shoot number and grain yield. However, high seed rate significantly increased the number of plots which experienced lodging ($P<0.05$). High seed rate had 18 out of 48 plots with lodging compared with 4 out of 48 plots for low seed rate (Table 5.13). Differences in crop growth caused by seed rate during stem extension, particularly for the early sown crops, appear to be linked with the differences in lodging.

Residual nitrogen

High residual nitrogen increased above ground dry weight, shoot number and green area index compared to low residual nitrogen ($P<0.05$) during early stem extension (GS 30 and GS 31). The influence of residual nitrogen on above ground dry weight and shoot number decreased as the season progressed and any effects were complicated by statistically significant high order interactions with the seed rate and lodging control treatments. At harvest high residual nitrogen caused a small, but statistically significant ($P<0.01$) increase in shoot number, from 503 to 520 shoots m^{-2}. However, no statistically significant differences were found for the above ground dry weight, grain yield or frequency of lodging at harvest.

Lodging controls

The PGRs 5C Cycocel and Terpal had little or no effect on crop growth. At GS 39 above ground biomass was significantly reduced by 5C Cycocel ($P<0.05$), but there was no statistically significant difference at harvest. In addition 5C Cycocel did not increase shoot number as found by other studies. Grain yield was not affected by PGRs. Out of 24 plots, lodging was experienced in nine plots for the nil lodging control treatment, five plots for 5C Cycocel and one plot for 5C Cycocel followed by Terpal.

At harvest Canopy Management significantly reduced above ground dry weight ($P<0.001$), shoot number from 527 to 468 shoots m^{-2} ($P<0.05$), grain yield from 9.5 to 9.2 t ha^{-1} ($P<0.001$), increased specific grain weight from 81.7 to 83.0 kg hl^{-1} ($P<0.001$) and increased thousand grain weight from 42.6 to 47.0g ($P<0.001$). It may be suggested that dry conditions reduced uptake of the late nitrogen application resulting in a smaller above ground dry weight. A similar number of plots lodged with and without Canopy Management, despite its smaller biomass. This may be due to the greater ear weight caused by this treatment.

5.4.5.3 The 1995-96 season

Growth and development of the high and low risk treatments

Development of the high risk treatment (1HN1 - early sown, high seed rate, high soil residual N and no PGR) was always ahead of the low risk treatment (2LO1 - late sown, low seed rate, low soil residual N and no PGR), but this difference decreased considerably towards harvest. The high risk treatment had a significantly greater above ground dry weight, shoot number and green area index from GS 30 to GS 39 ($P<0.05$; Figure 5.8). There was a large variation in the per cent area lodged, with 93 % in the high risk treatment and only 8 % in the low risk treatment (Table 5.15). Almost all of the lodging observed was root lodging which occurred early (GS 58 onwards) and continued to occur sporadically until harvest. At harvest above ground dry weight and shoot number were similar for the high and low risk treatments. However, most other high lodging risk treatments had greater dry weights and shoot numbers than the low lodging risk treatments. The severe early lodging which occurred in the high lodging risk treatment may have curtailed growth, similar to observations in the 1994-95 experiment. This could account for its small above ground dry weight, shoot number and grain yield (Table 5.14) at harvest compared with other high risk treatments, which lodged less severely.

(a)

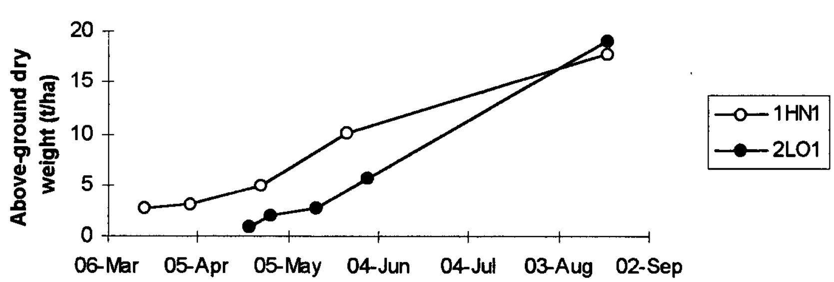


Fig. 5.8a

(b)

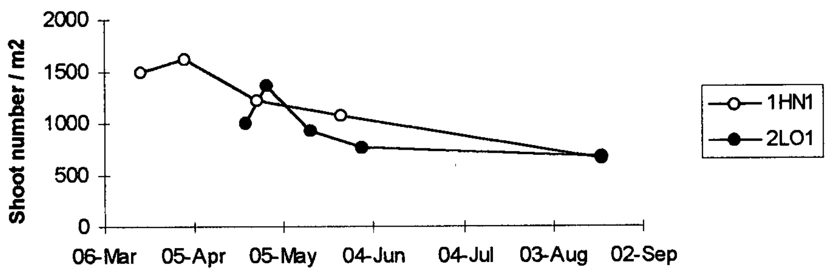


Fig. 5.8c

(c)

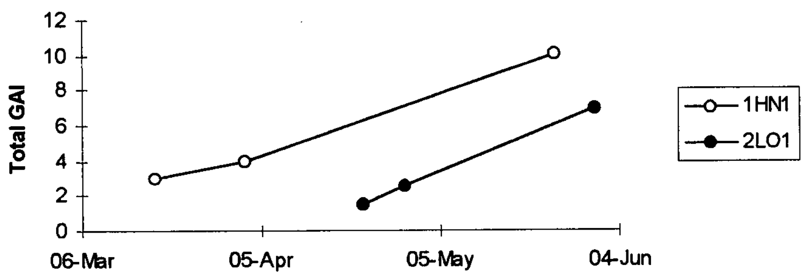


Fig. 5.8d

Figure 5.8 (a) Above-ground dry weight, (b) fertile shoot number and (c) total green area index with time for the high lodging risk (1HN1) and low lodging risk (2LO1) treatments in the 1995-96 experiment.

Table 5.14 Grain yield (t ha^{-1}; at 85% dry matter) for the 1995-96 experiment.

Treatments		**20 September sowing**		**1 November sowing**	
		500 seeds m^{-2}	**250 seeds m^{-2}**	**500 seeds m^{-2}**	**250 seeds m^{-2}**
High	Nil spring lodging control	8.1	9.4	10.1	10.1
soil	5C Cycocel (PGR)	10.1	10.0	9.8	10.1
residual	5C Cycocel + Terpal (PGR)	9.5	9.7	9.9	9.5
nitrogen	Canopy Management	9.1	9.3	9.2	9.0
Low	Nil spring lodging control	9.7	10.3	10.1	10.3
soil	5C Cycocel (PGR)	10.4	10.2	10.0	9.9
residual	5C Cycocel + Terpal (PGR)	9.8	10.0	10.1	10.1
nitrogen	Canopy Management	8.7	8.9	9.9	9.5

SED = 0.36 (56 df)

Table 5.15 Percent area lodged at harvest in the 1995-96 trial.

Sowing date	Seed rate	Soil residual N	Lodging control	**Total % area lodged**	% area leaning (5-45°)	% area (45-90°)	% area lodged flat
EARLY SOWING	HIGH SEED RATE	High soil residual N	Nil	**93**	0	6	87
			5C Cycocel	**88**	28	33	27
			5C + Terpal	**45**	20	15	10
			Canopy Man.	**80**	37	37	7
		Low soil residual N	Nil	**83**	33	38	12
			5C Cycocel	**40**	25	13	2
			5C + Terpal	**7**	6	1	0
			Canopy Man.	**23**	22	2	0
	LOW SEED RATE	High soil residual N	Nil	**87**	18	17	52
			5C Cycocel	**52**	18	17	17
			5C + Terpal	**15**	10	5	0
			Canopy Man.	**47**	23	24	0
		Low soil residual N	Nil	**40**	27	13	0
			5C Cycocel	**9**	6	3	0
			5C + Terpal	**3**	3	0	0
			Canopy Man.	**7**	5	2	0
LATE SOWING	HIGH SEED RATE	High soil residual N	Nil	**54**	12	12	30
			5C Cycocel	**7**	7	0	0
			5C + Terpal	**4**	1	3	0
			Canopy Man.	**0**	0	0	0
		Low soil residual N	Nil	**44**	10	11	23
			5C Cycocel	**3**	2	1	0
			5C + Terpal	**1**	1	0	0
			Canopy Man.	**5**	3	2	0
	LOW SEED RATE	High soil residual N	Nil	**14**	5	9	0
			5C Cycocel	**4**	4	0	0
			5C + Terpal	**1**	1	0	0
			Canopy Man.	**0**	0	0	0
		Low soil residual N	Nil	**8**	5	3	0
			5C Cycocel	**3**	2	1	0
			5C + Terpal	**0**	0	0	0
			Canopy Man.	**1**	1	0	0

The influence of husbandry on crop growth and lodging

Sowing date

The early sown treatment had a greater above ground dry weight, green area index and shoot number than the late sown treatment ($P<0.05$) from GS 30 to GS 39. The differences in above ground dry weight and shoot number were maintained until harvest, when early sowing produced an average above ground dry weight and shoot number of 17.7 t ha^{-1} and 774 shoots m^{-2} compared with 15.7 t ha^{-1} and 691 shoots m^{-2} for late sowing. Early sown crops also and a greater percentage area lodged per plot ($P<0.001$;Table 5.15). The early sown plots had on average 45 % area lodged compared with only 9 % for the late sown plots. Early sowing caused a slight reduction in grain yield from 9.85 to 9.56 t ha^{-1} ($P=0.093$;.Table 5.14). The yield reducing effect of severe lodging probably caused this effect.

Seed rate

High seed rate significantly increased the above ground dry weight, green area index and shoot number compared with the low seed rate ($P<0.05$) at GS 30 to 33. At GS 39 only shoot number showed large differences between seed rates ($P=0.054$). By harvest no statistically significant differences were found for above ground dry weight and shoot number due to seed rate. Despite this, high seed rate plots had on average 36 % area lodged compared with 18 % area lodged for low seed rate plots ($P<0.05$).

Residual nitrogen

High residual nitrogen increased above ground dry weight, shoot number and green area index ($P<0.05$) from GS 30 to 33. However, at GS 39 and harvest high residual nitrogen had ceased to increase crop growth. At harvest high residual nitrogen was associated with a greater per cent area lodged (37 %) compared with low residual nitrogen (17 %) ($P<0.001$). High residual nitrogen was also associated with a decrease in the above ground dry weight ($P<0.05$) and decreased grain yield from 9.86 to 9.54 t ha^{-1} ($P<0.001$). These effects may have been due to lodging reducing late crop growth in the high residual nitrogen crops.

Lodging controls

The PGRs 5C Cycocel and Terpal did not affect above ground dry weight, shoot number or green area index. The percent area lodged was significantly decreased from 53 % to 26 % by 5C Cycocel and further to 9 % by 5C Cycocel with Terpal ($P<0.001$). Canopy Management reduced the percent area lodged from 53 % to 21 % ($P<0.001$). However, this treatment also significantly reduced the harvest above ground dry weight ($P<0.001$), shoot number ($P<0.001$) and grain yield by about 0.5 t ha^{-1} ($P<0.001$). The Canopy Management treatment had a greater thousand grain weight ($P<0.001$). This indicates that at grain filling there was more than enough assimilate to fill the grain sites, but there may not have been adequate grain sites to fill. This could be due to either the formation of too few ears or too few fertile grain sites per ear. Canopy Management treatment received 150 kg ha^{-1} N less than the conventional treatments which more than covers the cost of the lost yield. Despite this low nitrogen application Canopy Management far exceeded its target green area index of five in many cases.

5.4.6 Summary of the three seasons

An assessment of crop growth in the 1993-94, 1994-95 and 1995-96 seasons can be gained by comparison with a 'bench mark' Mercia crop, as described in the 'Wheat Growth Guide' (Sylvester-Bradley *et al.*, 1998a). Information for this guide was compiled from data on the growth and development of Mercia from 18 site seasons, of which the early sown, high seed rate, high residual nitrogen, with 5C Cycocel and Terpal treatment of the 1994-95 experiment formed one site season. Growth data from this treatment and from identical treatments in the 1993-94 and 1995-96 experiments have been compared with the 'bench mark' wheat crop in Table 5.16.

Table 5.16 Comparison of crop growth and development from the 1993-94, 1994-95 and 1995-96 experiments with the 'bench mark' wheat crop, described in the 'Wheat Growth Guide' (Sylvester-Bradley *et al.*, 1998a).

	Bench mark crop	1993-94	1994-95	1995-96
Sowing date	*7 October*	16 October	23 September	20 September
Spring plant number m^{-2}	*302*	197	470	449
GS 31 date	*30 April*	-	22 March	2 April
GS 31 green area index	*1.9*	-	1.7	3.0
GS 31 dry weight t ha^{-1}	*1.6*	-	1.0	2.7
maximum shoot number m^{-2}	*978*	1137	829	1989
GS 39 date	*23 May*	20 May	12 May	24 May
GS 39 green area index	*5.9*	6.4	6.6	10.1
GS 39 dry weight t ha^{-1}	*6.6*	7.4	8.2	10.1
Harvest ear number m^{-2}	*604*	636	540	848
Harvest dry weight t ha^{-1}	*17.4*	19.1	17.2	18.1
Harvest grain yield t ha^{-1}	*9.1*	10.2	9.6	9.8

It must first be noted that the crops of the 1994-95 and 1995-96 experiments had about 50 % more plants established than the 'bench mark' wheat crop. This may be expected to increase growth at early stages of development. Growth in the 1993-94 season was about average at GS 39, but finished with a much greater above ground dry weight and grain yield. Early growth (GS 31) was smaller in the 1994-95 season, but after a slow start growth in this season caught up that of the bench mark wheat crop to finish with a similar above ground dry weight but even with a smaller ear number yield was still above the bench mark. Crop growth in the 1995-96 season was considerably greater than the benchmark crop throughout the season resulting in an increased yield, although still not as high as the 1993-94 crop.

5.4.6.1 A summary of the influence husbandry

The 1993-94 experiment showed little or no differences in crop growth between the high and low lodging risk treatments throughout the season. By comparison large differences were generated in the 1994-95 and 1995-96 experiments. These differences were greatest in the 1995-96 experiment, for which they existed throughout the growing season. However, growth differences in the 1994-95 experiment diminished as harvest approached. The lodging observed in the high risk treatment was more severe in 1995-96 than in 1994-95. Lodging in the high risk treatment is thought to have reduced late growth, causing a reduction in above ground dry weight and grain yield in both experiments.

Early sowing increased lodging in the 1994-95 and 1995-96 experiments. Small differences in crop growth due to sowing date were only observed during the early part of the 1994-95 experiment season, compared with large differences throughout the 1995-96 experiment season. The effects of seed rate and residual nitrogen on lodging were slightly less than the sowing date effects. High seed rate increased lodging in both experiments and high residual nitrogen increased lodging in the 1995-96 experiment. In general, both treatments increased crop growth between GS 30 and GS 39, but caused little or no differences in above ground dry weight or shoot number at harvest, in either experiment. Importantly, it was found that lodging could be considerably reduced by different combinations of sowing date, seed rate and residual nitrogen without remedial controls and without reducing grain yield. In fact the treatments with a perceived high yield potential had the lowest yields, which was probably due to the severe lodging they experienced.

PGRs reduced lodging in both experiments (although not statistically significant in 1994-95). However, they had no consistent effect on crop growth in terms of above ground dry weight, shoot number or green area index. Canopy Management reduced lodging in the 1995-96 experiment, this may have been due to its smaller above ground dry weight and shoot number. This treatment was also associated with reduced grain yield, although this may have been peculiar to these experiments since other research has shown little or no yield loss with this management practice. However, even in the 1995-96 experiment some Canopy Management treatments reduced lodging whilst causing little or no yield loss.

5.4.7 Conclusions

In all three seasons the summer weather conditions were not conducive to lodging, yet the 1995-96 experiment experienced considerably more lodging. It would appear that greater early crop growth, in terms of above ground dry weight, shoot number and green area index, brought about by the different environmental conditions during the early part of the 1995-96 growing season may have increased lodging risk. This coupled with slightly wetter conditions in the summer of 1996 probably explain why considerable amounts of root lodging were experienced in 1995-96 compared with small amounts of stem lodging in 1994-95 and small amounts of root lodging in 1993-94. These experiments have shown that husbandry has a very large influence on crop structure and lodging. However, it should be noted that the early season crop structure differences have often diminished or disappeared when lodging occurs. It therefore appears that early season differences in crop growth may be indirectly linked with differences in lodging severity later in the season. To fully understand how husbandry affects lodging the mechanism by which it alters crop growth must be elucidated.

It has been shown in Chapter 4 that the occurrence of stem or root lodging is determined by an interaction of the weather with the plant components of lodging: **leverage force, stem strength and anchorage strength**. These components have been shown to be influenced by a relatively small number of plant characters. It appears likely that husbandry can affect lodging indirectly by influencing the growth of these lodging associated plant characters. This is investigated in Chapter 6.

6. THE CAUSES OF LODGING

6.1 PLANT CHARACTERS WHICH AFFECT LODGING

The influence of weather, soil and crop parameters on lodging risk is demonstrated in Table 4.2. This shows that the range of crop parameters normally encountered in the UK are as important as the weather conditions during the lodging period in determining lodging risk. Soil characteristics such as clay content and structure (visual score) also significantly affect root lodging risk. The plant characters which influence lodging most include: **centre of gravity height, natural frequency, number of shoots per plant, stem radius, stem failure stress and root plate spread**. These plant characters are used by the lodging model to calculate the four components of lodging: leverage force of the shoot and plant, and the stem and anchorage strengths Table 6.1. It is envisaged that husbandry affects lodging risk by altering these lodging associated plant characters and the components of lodging.

Table 6.1 Lodging components and the plant characters used to calculate them

Lodging component	Influencing plant characters
Shoot leverage force	Natural frequency Centre of gravity height
Plant leverage force	Shoot number per plant Natural frequency Centre of gravity height
Stem strength	Stem radius Stem wall width Stem failure yield stress
Anchorage strength	Root plate spread Structural rooting depth

This chapter uses the model of lodging described in Chapter 4 to examine *how* sowing date, seed rate, soil residual N, plant growth regulators, disease and variety influence the relationship of the plant with its environment to affect lodging risk. This has been achieved by comparing the four components of lodging and their associated plant characters for plants grown under different husbandry inputs. Some of this work has been written in greater detail in a PhD thesis (Griffin, 1998). It is envisaged that a better understanding of the mechanisms by which husbandry affects lodging will improve lodging control, either through plant breeding, through changing cropping strategies and better targeting of lodging controls. It should be noted that an investigation of varieties was not one of the original objectives of this project, however it was felt that a cursory analysis would be of great value.

Full details of how the shoot and plant base bending moments, anchorage failure moment and stem failure moment are calculated are given in Chapter 4. The wind gust velocity (V_g) which is exceeded one per cent of the time and the daily rainfall exceeded one per cent of the time were set at $13ms^{-1}$ and 12 mm respectively to calculate the wind induced base bending moment and anchorage strength.

6.2 SOWING DATE, SEED RATE, SOIL RESIDUAL N, LODGING CONTROLS & DISEASE

6.2.1 Shoot and plant leverage force

Shoot leverage force was significantly increased by the early sowing, high seed rates and high levels of residual N (Table 6.2; Figure 6.1). A combination of sowing early at a high seed rate on a fertile site produced the greatest shoot leverage force of 73 Nmm. This contrasted with a shoot leverage force of 44 Nmm for a crop sown later, at a moderate seed rate, on a less fertile site. All lodging controls significantly reduced shoot leverage across sowing date, seed rate and residual N treatments (Table 6.2; Figure 6.2). An application of 5C Cycocel followed by Terpal reduced the shoot leverage force of the early sown, high seed rate and high soil residual N crop from 73 Nmm to 45 Nmm. This was a slightly smaller reduction than was achieved through altering cropping practice.

The role of high centre of gravity and low natural frequency in causing a large leverage force is shown in Table 6.2a and b. In the 1995-96 experiment, early sowing significantly increased centre of gravity height and decreased natural frequency, high seed rate decreased natural frequency, and high levels of residual nitrogen decreased natural frequency whilst showing a trend towards causing a higher centre of gravity. Sowing date had the largest effect on height at centre of gravity and natural frequency. On average, early sowing increased height at centre of gravity from 42 cm to 47 cm and decreased natural frequency from 91 Hz to 74 Hz, compared with late sowing. Lodging controls consistently decreased centre of gravity height whilst increasing natural frequency. 5C Cycocel followed by Terpal produced the greatest effect by reducing height at centre of gravity from 48 cm to 41 cm and increasing natural frequency from 72 Hz to 93 Hz.

This indicated that both plant characters are important in causing the changes in shoot leverage force due to different husbandry. Shoot leverage force could not be calculated for 1994-95 because its component plant characters were measured at different growth stages (height at centre of gravity at GS 67-69 compared with natural frequency at GS 85). However, height at centre of gravity and natural frequency were influenced by sowing date, seed rate, residual N and the lodging controls (Table 6.2a) in a similar way to 1995-96, thus indicating that these treatments will affect shoot leverage force in a similar way to that already described.

The plant leverage force was significantly altered by seed rate in 1995-96 (Table 6.2b), from an average of 145 Nmm for plants grown at high seed rate to 200 Nmm (Figure 6.3) for the moderate seed rate. This was a direct result of the significant change in shoot numbers per plant (Table 6.2b) which increased from an average of 3.1 for the high seed rate to 4.5 for the low seed rate. On average, all lodging control treatments significantly reduced the plant leverage force from about 210 Nmm to 160 Nmm (Figure 6.4). However, the mechanisms by which these reductions were achieved were different. The early PGR, 5C Cycocel, reduced plant leverage force due to a reduction in shoot leverage force (described earlier) and a significant reduction in shoot number per plant (P<0.05). The 5C Cycocel followed by Terpal treatment caused a similar sized reduction through the reduction of shoot leverage force alone. The Canopy Management treatment reduced the leverage force mainly through a reduction in shoot number per plant, which was reduced on average from 4.0 to 3.5 shoots. Similar treatment effects on shoot number per plant were found in 1994-95 (Table 6.2b) suggesting that the response of plant leverage force would have been similar in both experiments.

Table 6.2 Results of analysis of variance on the shoot and plant leverage forces together with the plant characters used to calculate them

	Sowing date		Seed rate		Level of residual N		Lodging control	
	94-95	95-96	94-95	95-96	94-95	95-96	94-95	95-96
(a) Shoot leverage force	a	* E > L	a	* H > M	a	* N > n	a	*** 0 > T
Centre of gravity height	NS	* E > L	NS	NS	*** N > n	P=0.09 N > n	*** 0 > T	*** 0 > T
Natural frequency	NS	* L > E	* M > H	* M > H	NS	* n > N	*** T > 0	** T > 0
(b) Plant leverage force	a	NS	a	** M > H	a	NS	a	*** 0 > C5
Shoot number per plant	NS	NS	*** M > H	*** M > H	* N > n	NS	* 0 > ?	* 0 > CN

*** for P = 0.001, ** for P = 0.01, * for P = 0.05 and NS for P >0.05.
E ~ early sown, L ~ late sown
H ~ high seed rate, M ~ moderate seed rate
N ~ high soil residual N, n ~ low soil residual N
0 ~ nil lodging control, 5C ~ 5C Cycocel, T ~ 5C Cycocel + Terpal, CM ~ Canopy Management.(The difference between the most extreme lodging control treatments are shown)
a - not possible to calculate

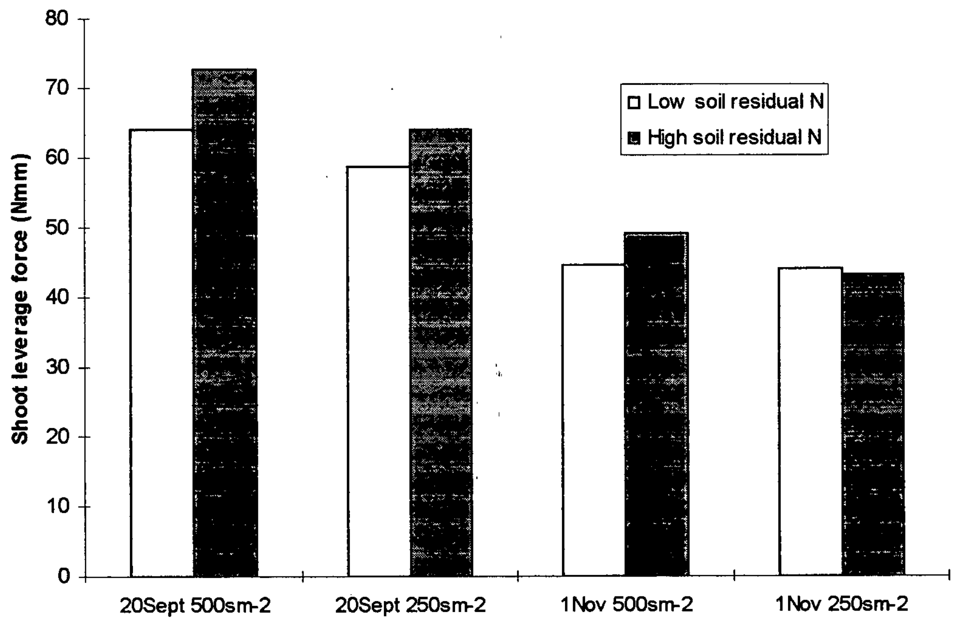


Figure 6.1 The influence of sowing date, seed rate and residual N on Shoot base bending moment in 1995-96. (Averaged across treatments).

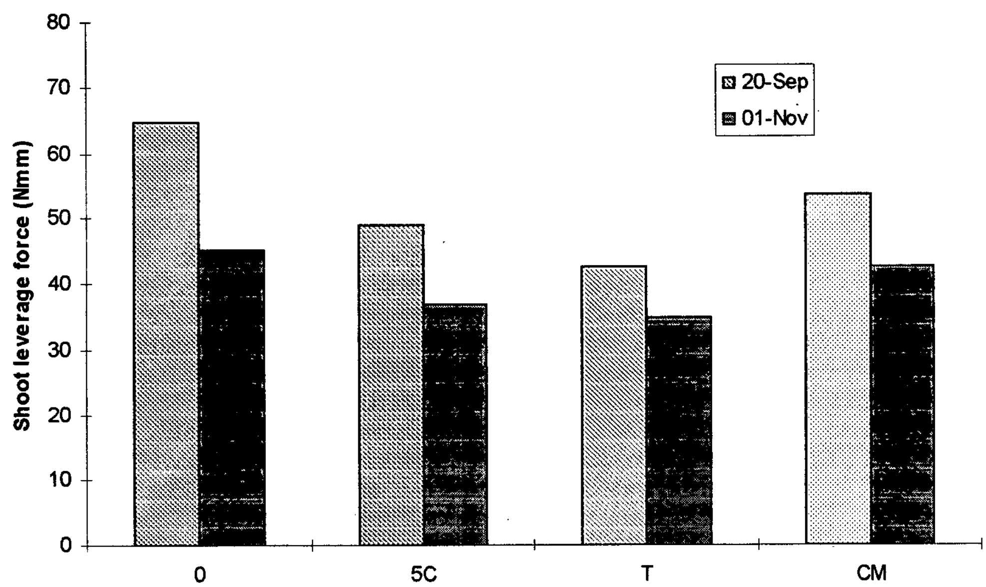


Figure 6.2 Influence of nil lodging control (0), 5C Cycocel (5C), 5C Cycocel + Terpal (T) and Canopy Management (CM) on Shoot base bending moment in 1995-96.. (Averaged across seed rate and residual N treatments).

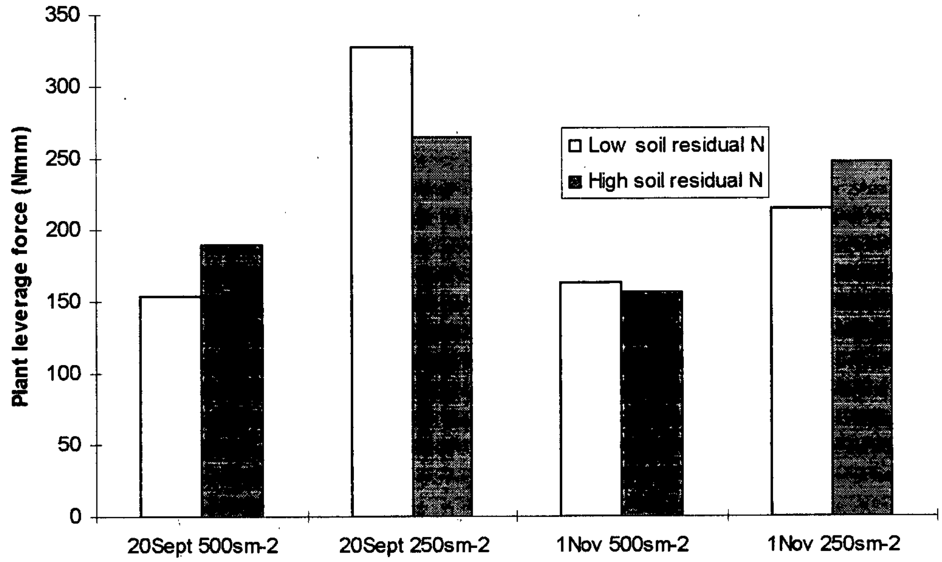


Figure 6.3 The influence of sowing date, seed rate and residual N on a) Plant base bending moment, for plants without lodging control in 1995-96.

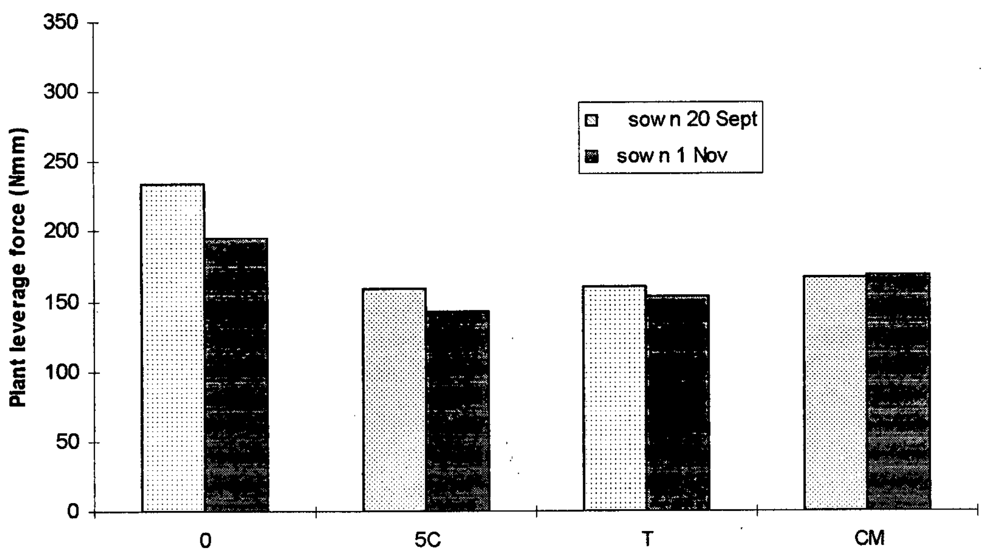


Figure 6.4 Influence of nil lodging control (0), 5C Cycocel (5C), 5C Cycocel + Terpal (T) and Canopy Management (CM) on Plant base bending moment of early and late sown crops in 1995-96 . (Averaged across seed rate and residual N treatments).

6.2.2 Stem base strength

A combination of early sowing on soils with high soil residual N produced the weakest stem bases (Table 6.3). The strength of the stem base varied from about 80 Nmm for crops sown early on high levels of soil residual N to about 160 Nmm for crops sown later on low levels of soil residual N (Figure 6.5). This significant interaction between sowing date and residual N was also found for all three components of stem strength, stem radius, stem wall width and stem material strength (Table 6.3). Seed rate had no statistically significant effect on stem base strength, despite high seed rates causing smaller stem radii.

5C Cycocel had no effect on the strength of the stem base (Table 6.3; Figure 6.6), although 5C Cycocel significantly decreased stem material strength. A statistically significant interaction was found between residual N and Canopy Management treatments for stem radius and wall width (P<0.05). In association with high levels of residual N, Canopy Management caused greater stem radii and wall widths compared with the Nil lodging control. For the early sown and high residual N treatment combination this resulted in stem failure moment increasing from 81 Nmm without Canopy Management, to 118 Nmm with Canopy Management (Figure 6.6). This represents an important method by which potential weak stems can be strengthened. Canopy Management had no effect on the strong stemmed later sown crops or on crops sown on soils with lower levels of residual N.

Table 6.3 Results of analysis of variance on stem base strength together with the plant characters used to calculate it for 1995-96.

	Sowing date	Seed rate	Level of residual N	Lodging control	Sowing date X Residual N	Residual N X treatment
Stem base strength	0.054 L > E	NS	** n > N	NS	** others > E+N	NS
Stem base radius	* L > E	* M > H	* n > N	NS	** others > E+N	** N+CN > N+0
Stem base wall width	** L > E	NS	** n > N	NS	P=0.091 others > E+N	* N+CN > N+0
Stem material strength	NS	NS	* n > N	* 0 > 5C	** others > E+N	NS

*** for P = 0.001, ** for P = 0.01, * for P = 0.05 and NS for P >0.05.
E ~ early sown, L ~ late sown
H ~ high seed rate, M ~ moderate seed rate
N ~ high soil residual N, n ~ low soil residual N
0 ~ nil lodging control, 5C ~ 5C Cycocel, T ~ 5C Cycocel + Terpal, CM ~ Canopy Management.
(The difference between the most extreme lodging control treatments are shown)

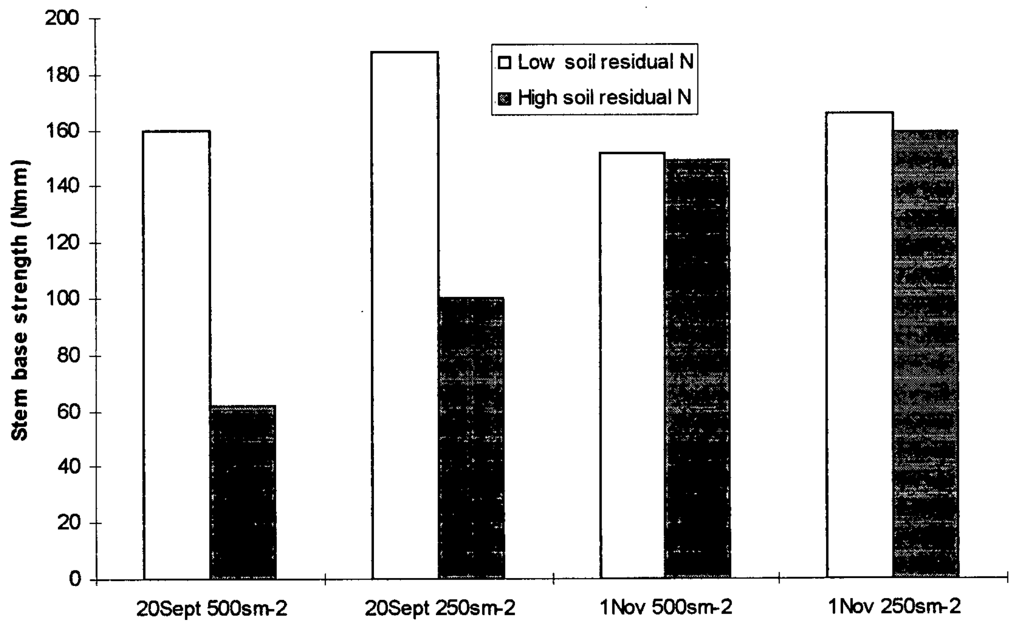


Figure 6.5 The influence of sowing date, seed rate and residual N on stem base failure moment for plants without lodging control in 1995-96.

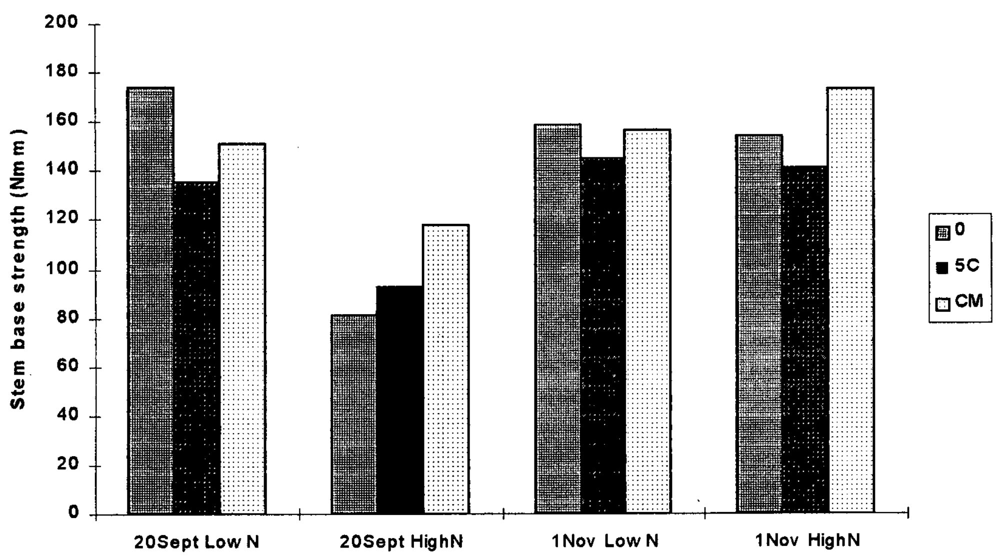


Figure 6.6 Influence of nil lodging control (0), 5C Cycocel (5C) and Canopy Management (CM) on stem base strength, for early and late sowings on both high and low residual N sites in 1995-96.

Results from the 1994-95 experiment (Table 6.4), showed that severe disease infection significantly reduced (weakened) internode 2. Stem strength was reduced by 32 Nmm (44%) for a severe fusarium infection, and by 25 Nmm (32%) for a severe sharp eyespot infection, compared with disease-free stems.

Table 6.4 The effect of stem base disease severity on stem failure moment at GS 87 in the 1994-95 experiment.

disease severity	Fusarium : IN2 stem failure moment (Nmm)	Sharp eyespot : IN2 stem failure moment (Nmm)
clean	72	72
slight	70	80
moderate	66	62
severe	40	49

(12df)	**SEM**	**p-value**	**cv%**	**LSD**
fusarium IN2	0.0053	<0.01	20.9	0.0163
s eyespot IN2	-	<0.01	7.6	0.0131

6.2.3 Anchorage strength

Anchorage strength and its components, root plate spread and structural rooting depth, were strongly increased by lower seed rates in both experiments (Table 6.5). However, variation between replicates for these rooting measurements was high. In 1995-96 coefficients of variation (cv) were 10% for structural rooting depth and 17% for root plate spread. These contrast with cv's of other lodging associated plant characters which were usually about 5%. For this reason values of anchorage strength were variable, with a cv of 30% in 1995-96.

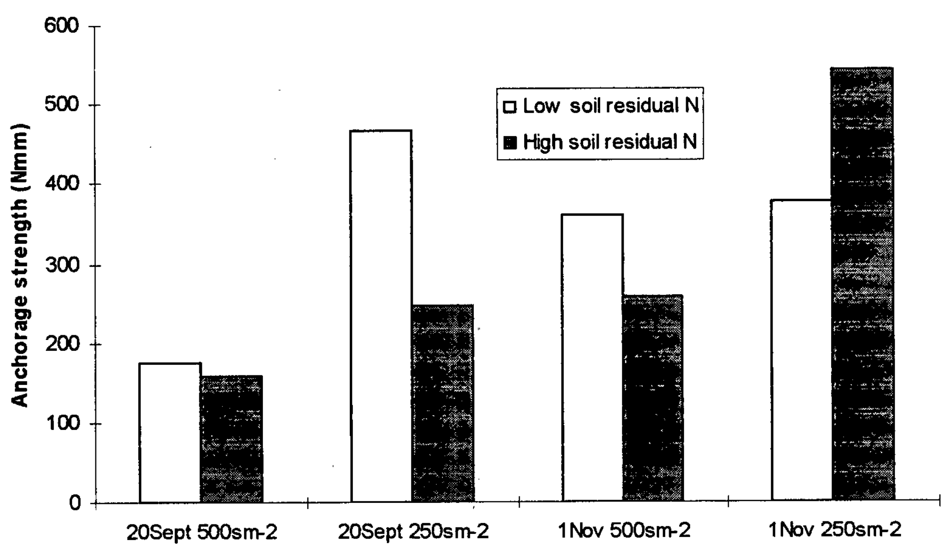
On average, anchorage strength increased from 239 Nmm for plants sown at a high seed rate to 409 Nmm for plants sown at low seed rate. There was a trend for crops sown later to have a greater root plate spread and anchorage strength in 1994-95 and 1995-96. This was probably due to the poorer plant establishment associated with the later sowing and might not have been a direct effect of sowing date. Plant establishment for the late sown crop was 77% in 1994-95 and 69% in 1995-96 compared with 90% and 95% for the early sowings respectively. In 1995-96 there was a trend for high levels of residual N to reduce anchorage strength and root plate spread. However, this trend was not found in 1994-95. Lodging controls had no significant effects on anchorage strength or its components in either experiment, although a trend was observed for 5C Cycocel to reduce anchorage strength in 1995-96. This effect may be related to an observation made earlier for 5C Cycocel to reduce shoot number per plant.

Table 6.5 Results of analysis of variance on anchorage strength together with the plant characters used to calculate it.

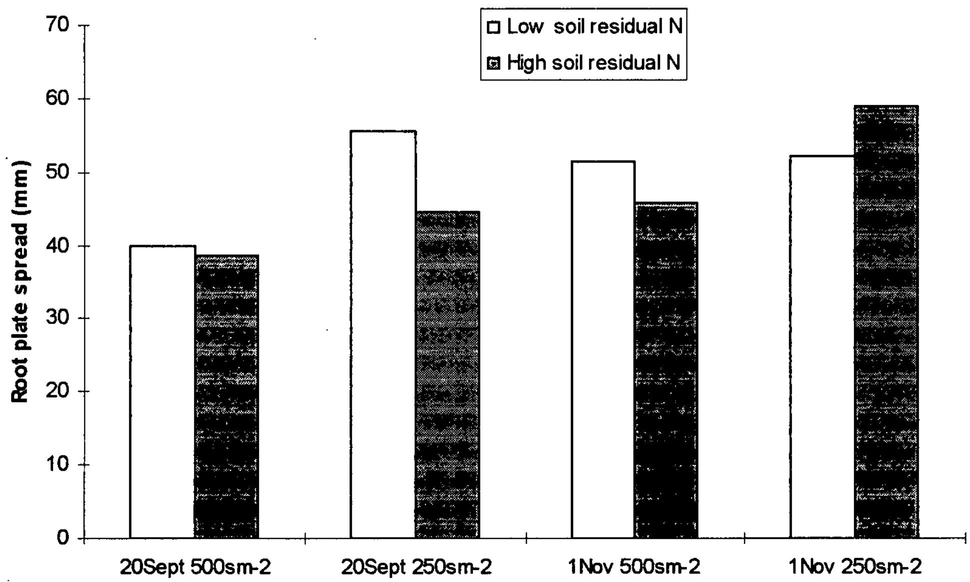
	Sowing date		Seed rate		Level of residual N		Lodging control	
	94-95	95-96	94-95	95-96	94-95	95-96	94-95	95-96
Anchorage strength	P=0.073 L > E	P=0.075 L > E	*** M > H	* M > H	NS	P=0.053 n > N	NS	P=0.064 0 > 5C
Root plate spread	P=0.094 L > E	P=0.059 L > E	*** M > H	* M > H	NS	P=0.066 n > N	NS	NS
Structural rooting depth	* E > L	NS	** M > H	** M > H	NS	NS	NS	NS

*** for P = 0.001, ** for P = 0.01, * for P = 0.05 and NS for P >0.05.
E ~ early sown, L ~ late sown
H ~ high seed rate, M ~ moderate seed rate
N ~ high soil residual N, n ~ low soil residual N
0 ~ nil lodging control, 5C ~ 5C Cycocel, T ~ 5C Cycocel + Terpal, CM ~ Canopy Management. (The difference between the most extreme lodging control treatments are shown)

(a)



(b)



(c)

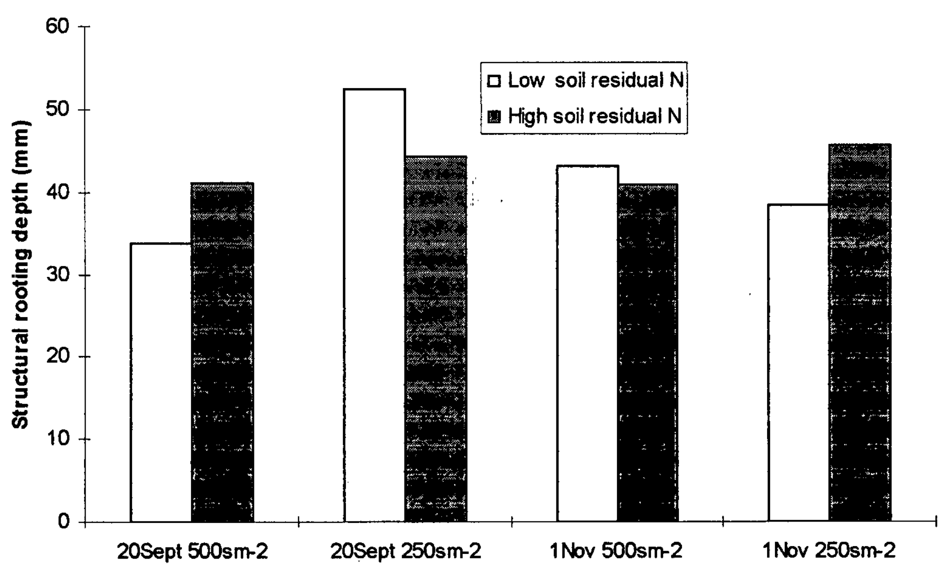


Figure 6.7 The influence of sowing date, seed rate and residual N on a) anchorage strength, b) root plate spread and c) structural rooting depth, for plants without lodging control in 1995-96.

6.2.4 Calculated lodging risks

The root lodging risk for the 1994-95 trial and the root, stem and total lodging risks for the 1995-96 trial, during a 40 day period between the end of June and beginning of August have been calculated by the lodging model (described in Chapter 4), and are shown in Table 6.6. A formal statistical analysis of stem, root and total lodging risk has not been undertaken due to the large number of zero lodging risks. Interpretation has instead been based on observation of the data.

It is apparent that the calculated 1994-95 root lodging risks were much higher than in 1995-96. This was due to the smaller root plate spreads observed in 1994-95. However, it has already been shown that more root lodging occurred in the 1995-96 experiment. This discrepancy is believed to have occurred for two reasons. Firstly, it seems likely that the dry soil conditions during the 1995 summer prevented extraction of the complete structural root system. Evidence for this is given by the decrease in root plate spread observed between GS 33 and harvest. This pattern of development does not agree with work by Crook *et al.* (1995) who found structural roots continued to grow until GS 39 and then did not change until harvest. This, more typical pattern of development was also found in the 1995-96 experiment which had a wetter summer and therefore better conditions for root extraction. It therefore appears that incomplete root extraction in the 1994-95 season, may have resulted in an underestimation of the root plate spread and anchorage strength, which caused a high root lodging risks to be predicted. Secondly, the actual weather conditions in the 1994-95 lodging period were less conducive to root lodging than in 1995-96. It must be remembered that the lodging risks shown in Table 6.6 are predicted using average weather conditions. In reality summers can be drier and less windy than average or wetter and windier than average. No account of this variation can be made because the likely weather conditions months in advance cannot be predicted. Thus in our experiments, less rain in the summer of 1995 resulted in drier and stronger soil and crops which were less prone to root lodging compared with 1996.

The predicted lodging risks given in Table 6.6 agreed well with the severity of lodging observed in the 1994-95 and 1995-96 experiments (Table 5.13 and Table 5.15). Sowing date caused the greatest difference in predicted and observed lodging severity. Seed rate and residual N effects were correctly predicted to be smaller. 5C Cycocel was predicted to reduce lodging more than Canopy Management in agreement with the lodging observed.

Table 6.6 Predicted lodging risks (probability of lodging in one season)

		94/95 Root lodging risk	95/96 Stem lodging risk	95/96 Root lodging risk	95/96 Total lodging risk
SOWING	Early	0.780	0.036	0.137	0.153
DATE	Late	0.570	0.001	0.002	0.002
SEED	High	0.770	0.034	0.077	0.094
RATE	Low	0.590	0.003	0.061	0.062
SOIL	High	0.660	0.037	0.094	0.111
RESIDUAL N	Low	0.690	0	0.044	0.044
LODGING	Nil	0.830	0.035	0.160	0.168
CONTROL	5C Cycocel	0.600	0.002	0.002	0.003
	Canopy Management	0.710	0.006	0.083	0.085

For 72 differently managed wheat plots the lodging model correctly predicted lodging in 21of the 30 lodged crops and nil lodging for 38 of the 42 standing crops. Thus the model could be said to be 82 % successful. These results give further confidence in the applicability of the model as a tool for predicting lodging.

Table 6.7 shows the PGR recommendation as calculated by the *ADAS crop centres winter wheat plant growth regulators – risk assessment chart* (Appendix 1) for differently managed wheat crops grown in the 1995-96 experiment. The site history was assumed to score –1, variety was Mercia which scored 6, a potential yield of 8-10 t ha^{-1} was expected and N was applied at the ADAS recommended rate and timing. The crops sown early, with a high plant population scored –1 regardless of soil fertility, for which a review of the cropping strategy was recommended to reduce lodging. The crops sown early, with a lower plant population of 205 plants m^{-2} scored +1, for which PGR sequences were recommended including split recommendations. The crop sown late with a plant population greater than 300 plants m^{-2} scored 3, and was deemed to have a very high lodging risk with PGR sequences recommended. The crop sown late, with a low plant population was deemed to have medium lodging risk, with a single PGR recommended.

The lodging experienced by these crops has been recorded in terms of the percent area lodged (Table 5.15) and the percent area lodged multiplied by the number of days it was lodged. The duration of lodging was included to give a better indication of lodging severity and potential yield loss. Fischer and Stapper (1987) have demonstrated yield loss to be directly related to the severity and duration of lodging.

The predicted lodging risk was calculated by the lodging model (as described in Chapter 4) and represents the probability of lodging occurring in one season given typical weather conditions.

It can be observed that the lodging experienced did not always relate well to the PGR recommendation. In addition, it appears that PGR sequences were recommended for crops which had a relatively low lodging risk. The lodging risk calculated by the lodging model was more accurate than the PGR scheme for estimating the ranking of lodging severity. One of the main shortcomings of the PGR guide is that it takes no account of the level of soil residual N. High N residues have been shown to increase lodging, even when spring N applications are tailored to the level of residual N as occurred in these experiments. By assessing the crop, the lodging model will be able to take account of these effects, as well as accounting more precisely for the effects of sowing date and plant establishment.

Table 6.7 A comparison of the PGR recommendation, observed lodging, and predicted lodging risk differently managed wheat crops

Sowing date	Plants Estab-lished (m^{-2})	Soil residual N	PGR recommed-ation (Appendix 1)	% area lodged (Table 5.15)	% area lodged x number of days lodged	Predicted lodging risk (Chapter 4)
20 Sept	467	High	-1	93	4468	0.58
20 Sept	467	Low	-1	83	1031	0.25
20 Sept	206	High	1	87	2117	0.39
20 Sept	206	Low	1	40	333	0.13
1 Nov	325	Low	3	44	283	0.01
1 Nov	160	Low	5	8	50	0

6.3 VARIETIES

The components of lodging were calculated for varieties of different standing powers grown in the 1994-95 season (Table 6.8). This shows that varieties have different susceptibilities to lodging for different reasons. e.g. it appears that Cadenza is susceptible to lodging due to its very poor anchorage. The moderate standing power of Spark despite its reasonable root anchorage is probably conferred by its very high leverage force. In addition very large varietal differences in the components of lodging are apparent e.g. plant leverage force can vary three fold and anchorage strength can vary by as much as five times between varieties. Thus large differences in the lodging susceptibility of different varieties should be expected.

At the time of measuring (mid anthesis) stem strength was always considerably greater that the shoot leverage force, thus suggesting that the risk of stem lodging was low at this stage of plant development. Work in this project has shown that as the plant ripens, stem strength can be halved and the shoot leverage force almost doubled. This will considerably increase the risk of stem lodging as harvest approaches and will probably make the varietal differences in shoot leverage force and stem strength more important.

Table 6.8 Varietal differences for the components of lodging.

Variety	standing power (NIAB)	shoot leverage force (Nmm)	stem base strength (Nmm)	Plant leverage force (Nmm)	Anchorage strength (Nmm)
Little Joss	poor	80	175	133	56
Maris Huntsman	poor	63	-	110	64
Cadenza	6	45	198	69	34
Apollo	6	-	-	-	64
Rialto	6	37	-	63	58
Mercia	6	35	236	64	76
Beaver	6	37	224	84	150
Rialto	6	37	-	63	58
Soissons	7	41	-	80	57
Spark	7	50	-	140	74
Hunter	7	36	-	52	67
Brigadier	7	36	-	61	81
Norman	7	-	-	-	89
Avalon	7	-	-	-	102
Riband	8	37	235	54	120
Hereward	8	36	205	67	109
Ami	-	36	-	80	51
Avital	-	44	-	104	89
Florin	-	34	-	63	53
Scipion	-	43	-	63	84
mean		*42*	*212*	*76*	*77*

6.4 DISCUSSION

The risk of stem lodging was increased most by a combination of sowing early on fertile soil, which dramatically reduced the strength of the stem base. These crops had larger canopies during the early stem extension period which may have caused the extending stems to etiolate, resulting in thinner and weaker stems (Mulder, 1954; Holmes *et al.*, 1960). This agrees with the smaller stem radii and wall widths associated with this treatment combination. However, the mechanism by which stem failure yield stress is affected would require further investigation. In support of Fielder (1988) early sowing also increased stem lodging risk by increasing centre of gravity height and the shoot leverage. Stem lodging risk was increased by severe infections of eyespot and fusarium which can reduce stem strength by between 30 and 45 %. This is likely to have been a contributory factor in causing the stem lodging experienced in the 1994-95 experiment. High seed rate is widely perceived to increase stem lodging risk by increasing plant height and by reducing stem strength (Easson *et al.*, 1993). However, this study showed that high seed rate only increased shoot leverage slightly and had no statistically significant effect on stem strength.

High seed rates exerted their greatest influence on lodging by reducing root plate spread and plant anchorage. High seed rates also reduced plant leverage force. However the decrease in plant leverage due to higher seed rates was proportionally smaller than the decrease in anchorage strength, thus leading to the conclusion that high seed rates increase root lodging risk. This hypothesis is reinforced when it is considered that plant leverage is calculated by multiplying the leverage of the main shoot by the number of shoots per plant. It is likely that primary and secondary tillers will have a smaller leverage than the main shoot, which may have resulted in an over estimation of plant leverage. This discrepancy would be greatest for low seed rate plants which have a proportionally greater number of secondary tillers. The association of later sown plants with greater anchorage strengths due to poorer plant establishment suggests that plant population may be an important indicator of plant anchorage. Finally, there was a trend for plant anchorage to be reduced by high levels of soil residual N. This trend was not statistically significant but supported work by Crook and Ennos (1995). This may explain why the high soil residual N treatments had more root lodging in 1995-96 despite the non significant effect of soil residual N on plant leverage.

Despite lodging being caused by different mechanisms, two of the most common forms of lodging control (5C Cycocel and Terpal) acted simply by reducing the leverage of the shoot and plant. Additionally, it was discovered that similar or greater reductions in leverage could be brought about by sowing later, at lower seed rates or on less fertile soils. In the absence of lodging such cropping strategies had no adverse effect on grain yield. One method of reducing stem lodging risk was Canopy Management, which in some instances increased stem strength by 50%. It is envisaged that reducing spring nitrogen applications, reduced the canopy size during early stem extension, which prevented excessive etiolation and weakened stem bases. Canopy Management also reduced root lodging risk through a smaller plant leverage.

However, grain yield losses of between 0.3 and 0.9 t ha^{-1} were associated with this treatment, albeit in two unfavourably dry seasons. Nonetheless these losses were partially or wholly offset by savings in N applied.

Data to calculate the NIAB 'standing power' is taken from trials which show some leaning or lodging. The scores from which standing power ratings are derived are averages of the percent of the area of a plot that has lodged (fallen more than 45°) plus the area that has leaned (between 5 ° and 45°) divided by three (an arbitrary constant set so that leaning can be related to lodging). The data are generally a rolling average of the last five years. They thus vary according to whether recent seasons and sites have experienced much lodging. Work in this project strongly suggests that varietal lodging resistance can be estimated by measuring specific plant characters associated with lodging. This would allow the 'standing power' of different varieties to be gained without relying on the occurrence of lodging conducive weather conditions. Furthermore, this approach would pinpoint why different varieties are susceptible to lodging; whether due to weak anchorage, weak stems or excessively high leverage forces. Such an understanding will allow breeders to better select lodging resistant varieties and will mean that growers can target lodging controls to suit individual varieties, e.g. a variety with poor anchorage might benefit most from sowing at a lower plant density or spring rolling, a variety with weak stems might benefit most from a stem strengthening PGR. On the other hand varieties may be better matched with their growing conditions e.g. well anchored varieties should be grown on soils with weak soil strength and strong stemmed varieties should be grown on fertile soils.

6.4.1 Conclusions

The influence of husbandry on lodging risk has been demonstrated to act through different mechanisms. The risk of stem lodging may be increased by greater shoot base bending moments or weaker stem bases, and the risk of root lodging may be increased by greater plant base bending moments or weaker anchorage. This means that remedial controls would be most effective if they were targeted at the specific cause of lodging. e.g. early sown crops have been shown to have large leverage forces due to greater plant height, and would benefit most from a growth regulator product timed to have the greatest effect on shortening the stem . Crops sown early on fertile soils are prone to weak stem bases which can be best rectified by reducing spring nitrogen applications or applying products which strengthen stems. High seed rate crops might benefit most from rolling to consolidate the soil and maximise their inherently poor anchorage. Finally, the most effective method of reducing lodging risk is by careful selection of cropping strategy. This was as effective as the lodging controls at reducing lodging risk and the lodging experienced, without compromising yield.

7. PREDICTING LODGING RISK

Results from the aerial photography survey (Chapter 2) and the scientific literature (Chapter 3) have shown that lodging risk is not just determined by the weather at the time of lodging, but also by crop structure which can be manipulated by cropping strategy. Chapter 4 showed that lodging risk is influenced by a relatively small number of plant characters. It was concluded in Chapter 5 that early season differences in crop growth affected lodging risk indirectly by influencing the growth and development of the lodging associated plant characters identified in Chapter 5. Chapter 6 has shown that husbandry has a strong influence on the lodging associated plant characters at the time of lodging. Thus there is strong evidence that spring crop assessments can be used to estimate lodging risk.

It is the aim of this chapter to test whether crop inspections in the spring, together with wider intelligence, can significantly improve the assessment of lodging risk. This aim has been approached by developing prediction schemes linking spring-time crop observations with the summer-time values of the plant characters associated with lodging. Such schemes could be used with the lodging model to give a prediction of the future lodging type and risk. This could be made in time for decisions on remedial controls (PGR and nitrogen applications and spring rolling) and would allow the most appropriate lodging controls to be applied.

An understanding of the development and growth of the lodging associated plant characters together with a knowledge of how husbandry affects these processes indicates that these plant characters can be predicted from observations of the spring crop. A flow diagram which summarises how this might work based on an understanding of wheat development and growth is shown in Figure 7.1. This indicates that just a few measurements of the crop in the spring may be used to estimate the summer-time values of the lodging associated plant characters. The information required about the spring crop includes canopy size, plant density, shoot density, the thermal time for one leaf to emerge (phyllochron), soil nitrogen supply and the number of leaves on the main stem. The next step has been to use experimental data from the lodging project to test and calibrate these prediction schemes. The work reported in this chapter is given in greater detail in a PhD thesis (Berry, 1998).

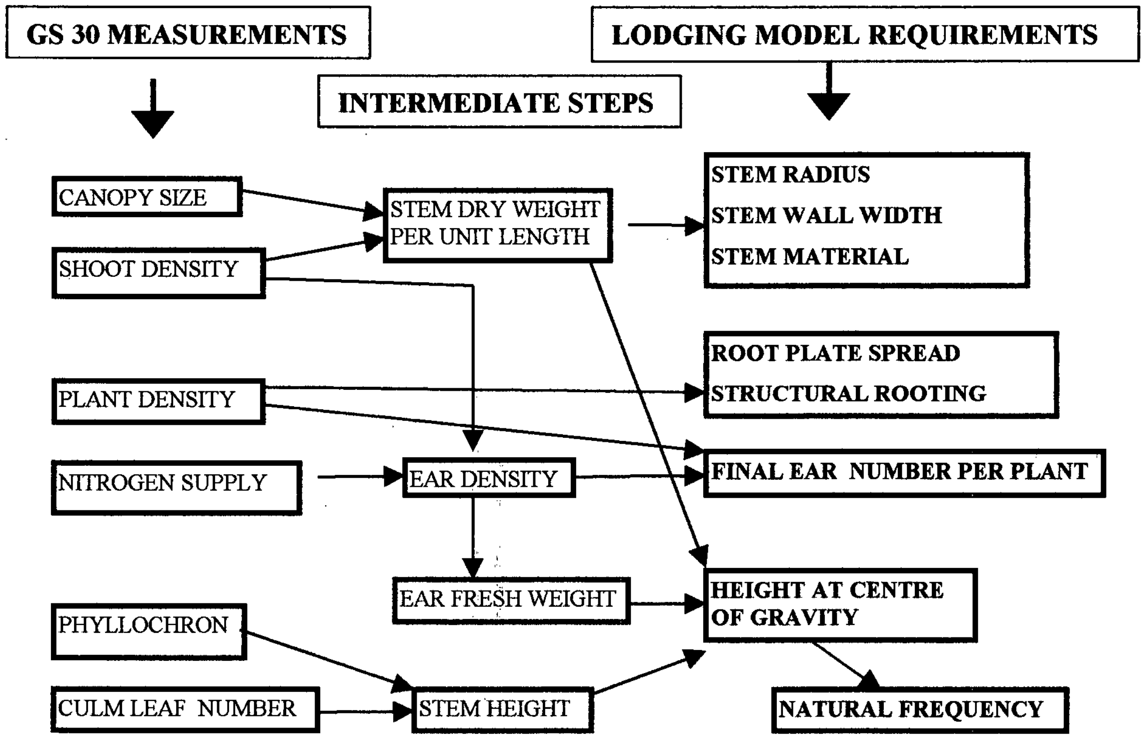


Figure 7.1 Illustration of how the summer-time values of lodging associated plant characters might be predicted from spring crop measurements and field observations.

7.1 PREDICTING ROOT ANCHORAGE STRENGTH

A detailed flow diagram of how root plate spread and structural rooting depth (used to calculate anchorage strength) may be related to spring crop measurements is shown in Figure 7.2. This predicts that root plate spread might be inversely related to plant density. This is because low plant densities are associated with greater rigid root lengths (Easson *et al.*, 1995) and plant base widths, both of which will increase root plate spread. This scheme has been tested with data from the lodging experiments. This shows a reasonable inverse correlation between spring plant population and root plate spread. Plant density also showed a similar but less significant correlation with structural rooting depth. These two relationships meant that spring plant density was negatively correlated with the summer-time anchorage strength (Figure 7.3). This relationship shows anchorage strength at 200 plants m^{-2} to be four times that at 500 plants m^{-2}. It appears that spring plant density will be a good indicator of anchorage strength, however this relationship must be tested with more varieties, at more sites and in more seasons before it can be used confidently.

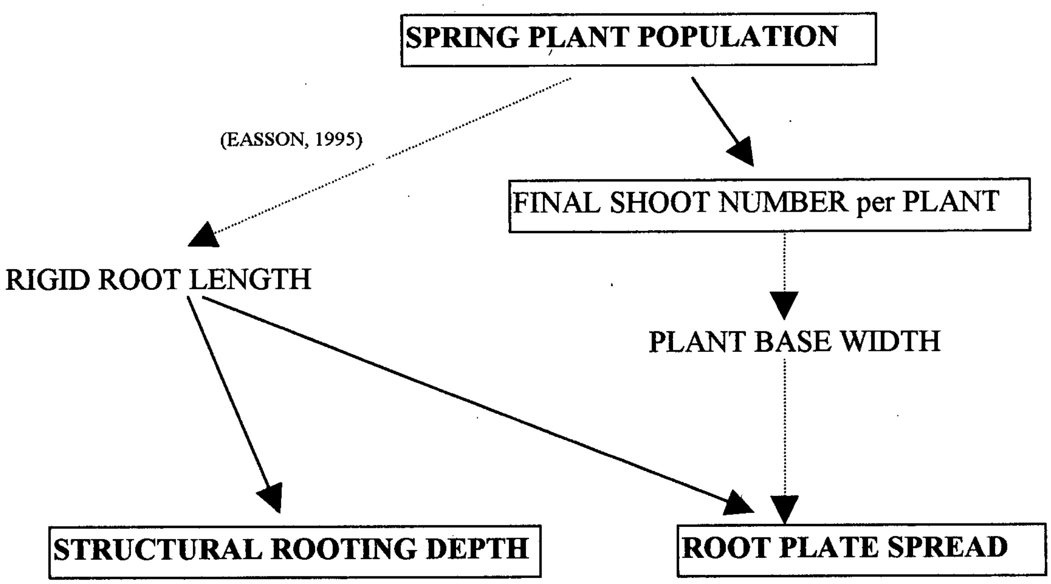


Figure 7.2 Schematic diagram outlining how the structural root characters could be related to spring plant measurements

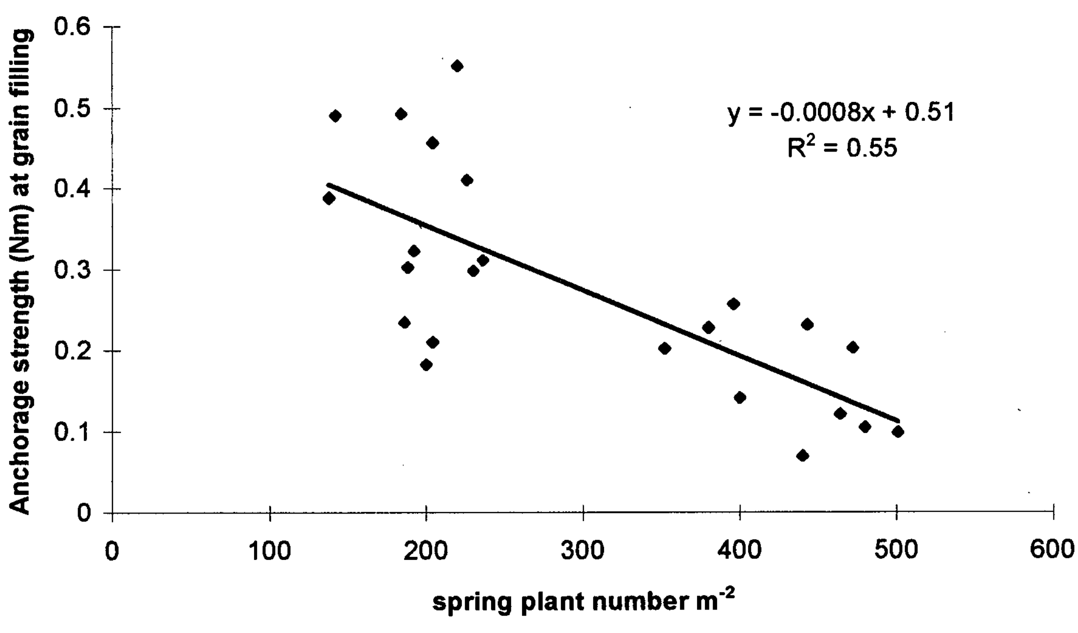


Figure 7.3 Spring plant number plotted against anchorage strength measured during grain filling.

The largest differences in structural rooting depth were due to season and genotype. Structural rooting depth measured at GS 30 predicted the seasonal differences reasonably well. This measurement would also be expected to account well for the genotypic differences, whose rankings remained constant between GS 30 and GS 61. However, this prediction assumes that structural rooting depth remains unchanged from GS 30 onwards. This is uncertain and there is evidence to suggest that structural rooting depth increases slightly after GS 30. If this was proven then the prediction scheme should be modified to take this into account.

Measurements of structural rooting depth taken at GS 30 did not account for variation within each season. This was probably because its natural variation was greater than its changes due to husbandry, e.g. the largest treatment difference (due to seed rate) was 6 mm, however differences between replicates could be as great as 15 mm. This probably explains why only the larger differences between seasons were accounted for. To predict the relatively modest differences in structural rooting depth due to husbandry, it appears that more precise measurements must be made. As with root plate spread, greater numbers of plants may need to be measured to reduce the large amount of variation associated with this character.

7.2 PREDICTING STEM STRENGTH

A detailed flow diagram of how two of the plant characters used to calculate stem strength, stem diameter (radius) and stem wall width, may be predicted from the spring canopy size and shoot number is shown in Figure 7.4. This scheme has been developed entirely from the scientific literature. The scheme assumes that stem radius and wall width are directly related to the amount of dry matter accumulated per unit length of the stem. The amount of dry matter accumulated per unit length of the stem is dependent upon the demand and supply of dry matter. The greater the dry matter demand in relation to the supply the less dry matter will be accumulated per unit length of the stem and the smaller its radius and wall width.

Dry matter demand is determined by the number of stems which are extending and their rate of extension. Large shoot numbers and rapid stem extension result in a high dry matter demand. The rate of extension is strongly influenced by the degree of canopy shade (Holmes and Smith 1977; Hayward, 1985; Morgan and Smith 1979), with large canopies causing stems to extend more quickly (etiolate).

Dry matter supply is determined by the amount of incident radiation which the wheat canopy can intercept (Monsi and Saeki, 1953; Thorne *et al.*, 1988), the efficiency with which this is converted to dry matter (Gallagher and Biscoe, 1978) and the proportion which is partitioned to the stem (Weir *et al.*, 1984; Foulkes *et al.*, 1993). Sunny conditions and large canopies will result in a high dry matter supply to the stems.

It can be seen that large canopies increase both dry matter demand and dry matter supply. The balance depends on the size of the canopy, with very large canopies increasing demand more than supply resulting in thinner weaker stems and vice versa.

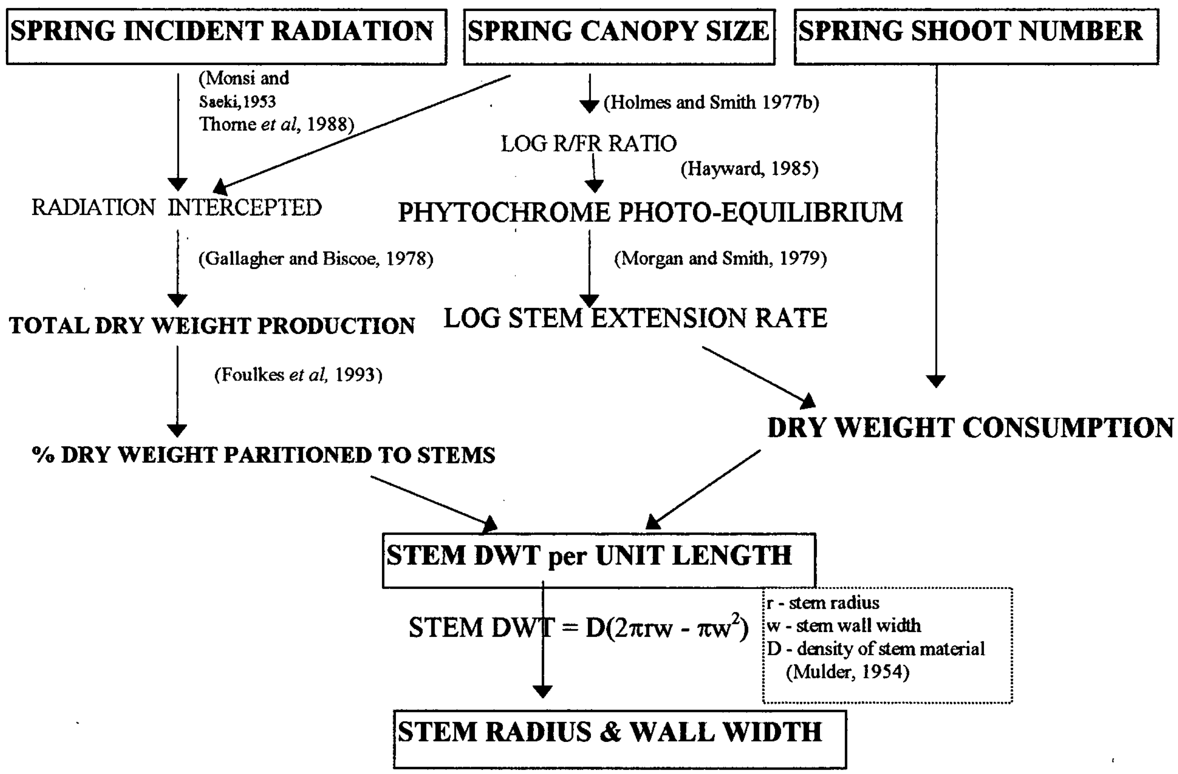


Figure 7.4 Schematic diagram outlining how stem radius and stem wall width could be predicted from spring plant measurements.

Measurements of GAI and shoot number taken at GS 31 have been used in the scheme described in Figure 7.4 to predict summer-time values of stem radius and wall width. To test how well this prediction scheme works the predicted values of stem radius and wall width have been compared with the observed values of stem radius and wall width in Figure 7.5 and Figure 7.6. These show that the two stem characters can be predicted reasonably well.

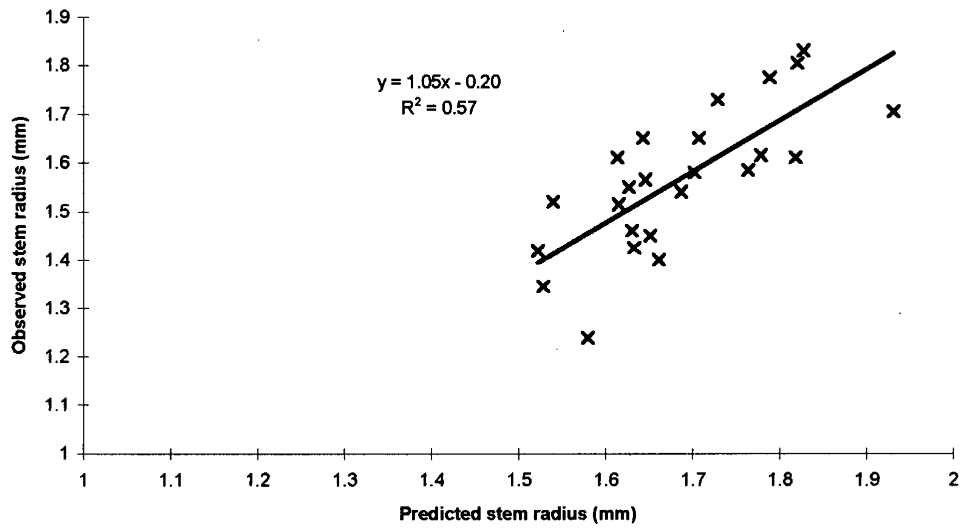


Figure 7.5 Predicted stem radii plotted against stem radii observed at GS 73 in 1995-96.

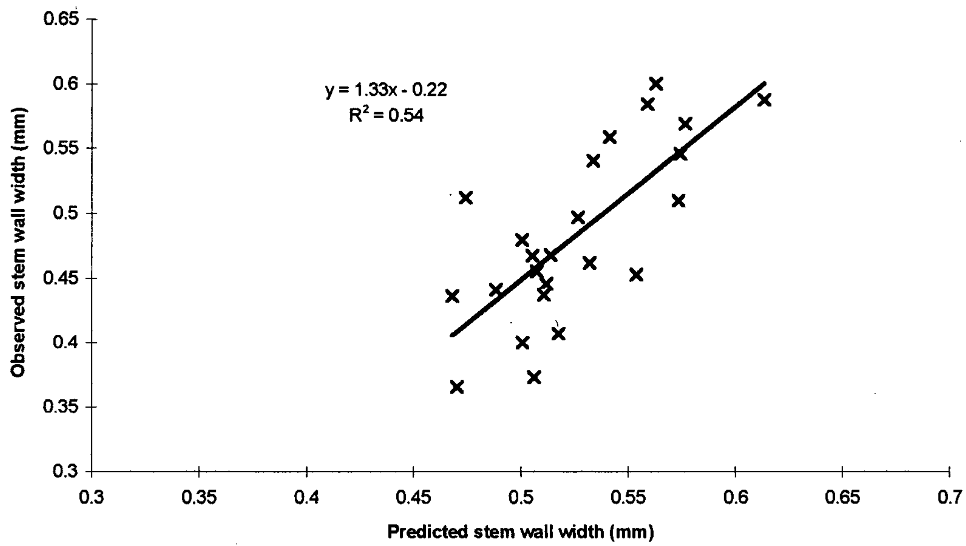


Figure 7.6 Predicted stem wall width plotted against stem wall width observed at GS 73 in 1995-96.

It has been shown that GAI and shoot number m^{-2} measured in the spring can be used to accurately predict summer-time values of stem radius and wall width. It was shown in Chapter 4 that stem radius and stem wall width are important components of stem strength. Thus, it is likely that spring measurements of GAI and shoot number m^{-2} may be used to calculate summer-time stem strength indirectly. They may also give an indication of summer-time stem strength directly. Figure 7.7 illustrates this by showing that GAI measured at GS 31 was negatively related with summer-time stem strength. This study also found shoot number m^{-2} to be positively related to GAI at GS 31, with approximately 500 shoots per GAI unit. This suggests that shoot number m^{-2} will also be negatively related with stem strength. However, it must be emphasised that the most precise estimate of stem strength will be gained by using spring measurements of both GAI and shoot number m^{-2} in the scheme outlined in Figure 7.4. It must also be recognised that further testing of this prediction scheme will be required before it can be used to predict stem strength with confidence.

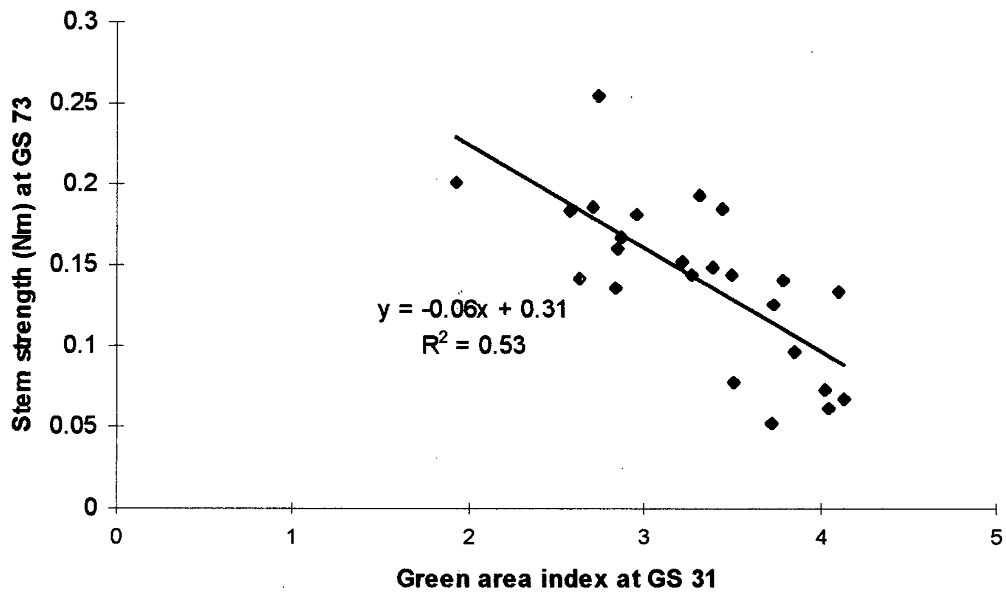


Figure 7.7 Green area index at GS 31 plotted against stem strength measured during grain filling.

Stem failure yield stress is the other plant character which is used with stem radius and stem wall width to calculate stem strength. This character is poorly understood and most of the experimental work was devoted to increasing its understanding. It varied independently of stem radius and wall width and showed large genotypic variation. There were also inconsistent effects for high residual nitrogen to decrease it. However, the mechanism by which this might occur is not yet understood. No other husbandry treatments appeared to affect it. To develop a prediction scheme for this character from GS 30 it appears that investigations as to the effect of genotype and residual N would be most beneficial. Importantly its value remained fairly constant from GS 33 or GS 39 until harvest, which suggests later predictions of this plant character could be relatively straight forward.

7.3 PREDICTING PLANT AND SHOOT LEVERAGE FORCE

Plant leverage force is calculated by multiplying the shoot leverage force by the number of shoots per plant. Shoot leverage force is calculated from natural frequency and centre of gravity height. In this section the prediction of shoot number per plant will be dealt with first followed by natural frequency and centre of gravity height.

7.3.1 Predicting shoot number per plant

A scheme which relates final shoot number per plant with values of the spring plant population and spring shoot number m^{-2} is described in (Figure 7.7). Firstly the spring shoot number m^{-2} is used in a model adapted from Porter (1984) to predict the shoot number m^{-2} at harvest. This model calculates the probability of each tiller surviving assuming that all main shoots survive, that tiller death rate is a function of shoot density, that the last formed tillers die first and that tiller death occurs between double ridges and anthesis. The limitations of this model are recognised especially as it does not account for the effect of nitrogen supply on tiller survival. The second step of this prediction scheme is to divide the predicted final shoot number m^{-2} by the spring plant population to give the final shoot number per plant.

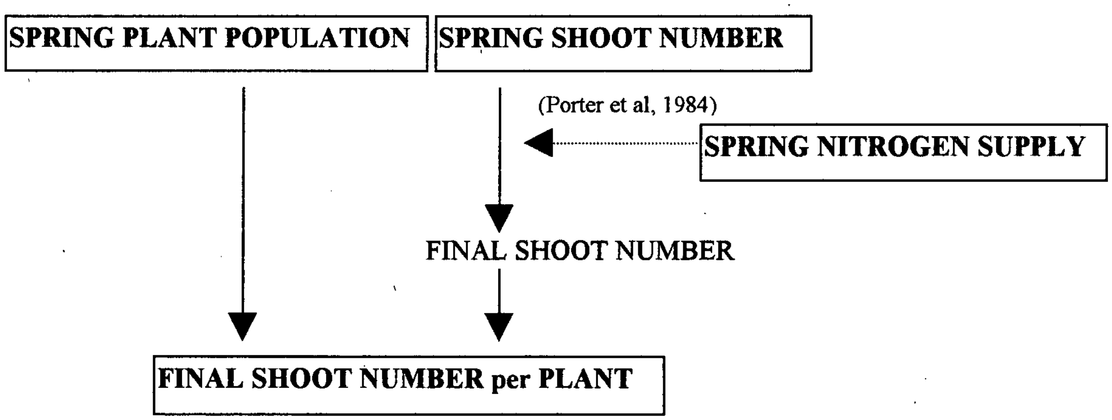


Figure 7.8 Schematic diagram outlining how shoot number per plant could be predicted from spring plant measurements.

Measurements of spring plant population and shoot number measured in the experiments described in Chapter 5 have been used in this scheme to predict final shoot number per plant. To test how well these predictions work the predicted shoot numbers per plant have been compared with the final shoot number per plant observed in the experiments (Figure 7.9). This shows that a very good relationship between the predicted and observed shoot number per plant. However, it must be noted that the experiments described here were all adequately supplied with nitrogen. It is probable that this scheme will be less accurate for crops which are nitrogen limited, or over fertilised. It is also known that shoot number varies significantly with variety, which is another factor which should be built into this scheme.

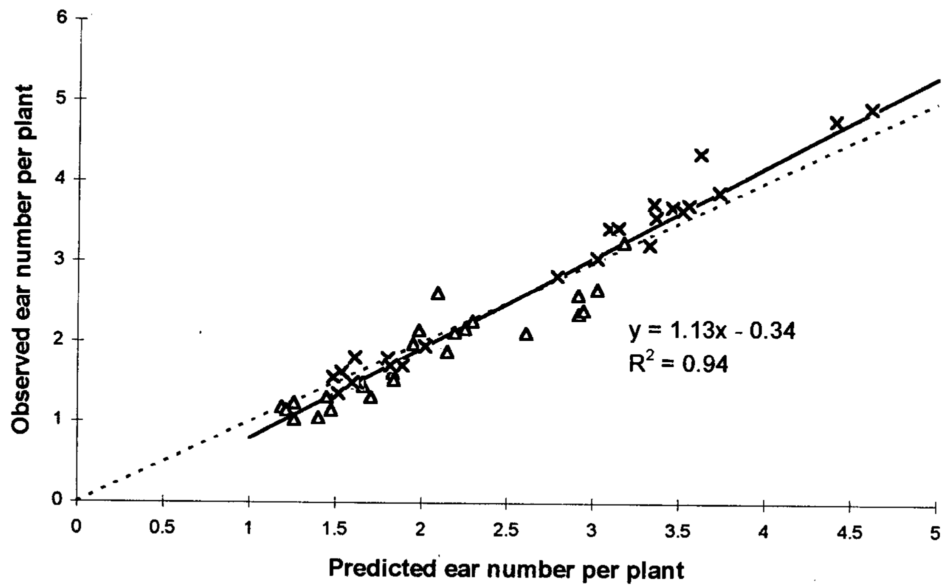


Figure 7.9 Predicted ear number per plant plotted against observed ear number per plant for the 1994-95 (Δ) and1995-96 (×) husbandry experiments. The ideal 1:1 relationship (---) and best fit line (—) are given.

7.3.2 Natural frequency and Centre of gravity height

Natural frequency is a complex plant character and is influenced by centre of gravity height, ear weight, stem stiffness and root ball resistance (Baker, 1995). It has been demonstrated by Baker (1995) that centre of gravity height is the most influential component of natural frequency. Increasing centre of gravity heights result in slower natural frequencies which cause a greater leverage force. This has been tested in the experiments (Figure 7.10) in which the inverse relationship between natural frequency and centre of gravity height has been quantified. It must be noted that natural frequency and centre of gravity height can vary independently e.g. high seed rate decreased natural frequency whilst having little or no effect on centre of gravity (section 6.2). Also this relationship must be further tested in other sites and seasons. However, it appears that generally a reasonable estimate of natural frequency can be gained from centre of gravity height. It is therefore envisaged that a prediction of centre of gravity will be very useful in predicting natural frequency and shoot leverage force.

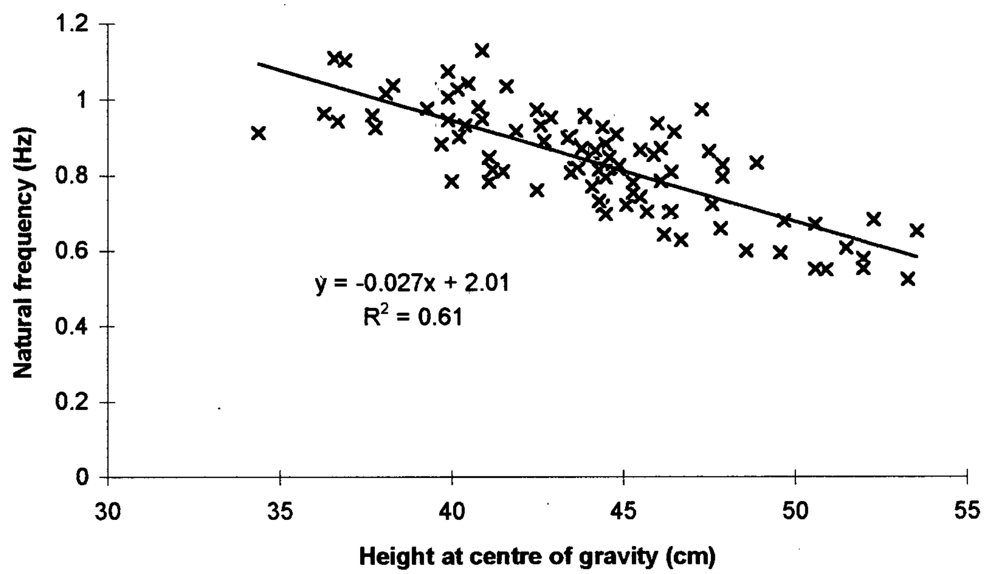


Figure 7.10 Height at centre of gravity plotted against natural frequency at GS 73 for all treatments in the 1995-96 experiment.

A simple formula of centre of gravity height has been developed in this study (Equation 7.1) which demonstrates that its main components are stem height, ear weight, leaf and stem weight and ear length.

$$X = \frac{(S_L S_W + 2S_L E_W + E_L E_W)}{2(S_W + E_W)} \qquad \textbf{(7.1)}$$

X - height at centre of gravity

S_L - stem height to ear bas

S_W - stem and leaf fresh weight

E_L - ear length

E_W - ear fresh weight

Schemes by which each of these components might be linked with spring crop measurements is outlined in Figure 7.11. The useful spring measurements include spring culm leaf number, phyllochron, spring shoot number m^{-2} and spring nitrogen supply. Some of the steps in the flow diagram have already been completed in other prediction schemes e.g. final shoot number per plant and stem dry weight. However, other steps have not been completed because at present understanding of wheat growth is not far enough advanced e.g. how quickly do internodes extend and for how long, or the prediction of grain number per ear. It will be the remit of further work to elucidate these mechanisms before robust prediction schemes of natural frequency and centre of gravity height can be developed.

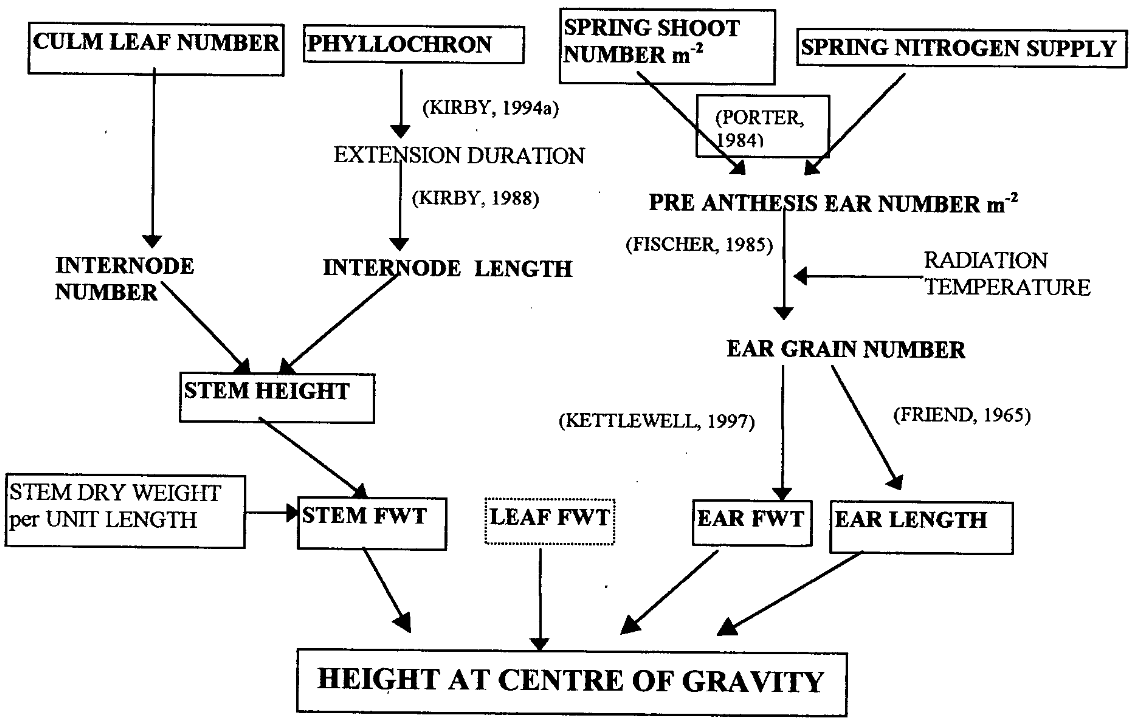


Figure 7.11 Schematic diagram outlining how the components of height at centre of gravity could linked with spring plant measurements.

7.4 DISCUSSION

The belief that early season crop assessments can give an indication of lodging risk appears to have been born out. The prediction schemes developed for the plant characters which influence lodging most (root plate spread, stem diameter and shoot number per plant) are based on sound principles and appear to give a reasonable indication of the summer-time values. All these prediction schemes have limitations, the most important being that they have not been tested with a wide enough range of sites, seasons, genotypes and husbandry practices. It is envisaged that each prediction scheme may include a constant to account for different varieties. Nevertheless, these schemes as they stand will improve upon current assessments of potential anchorage failure moment, stem failure moment and plant base bending moment, and so improve lodging control.

Prediction schemes for the other lodging associated plant characters are less important, but nevertheless crucial if an accurate and quantitative prediction of lodging risk is to be developed. Understanding of structural rooting depth, stem failure yield stress, natural frequency and centre of gravity height has been greatly advanced, but further investigations are necessary. It appears that GS 30 measurements of structural rooting depth might correspond to summer-time values. Stem failure yield stress may best be measured later at GS 33 or GS 39, in time for decisions about mid window and late PGRs. Theoretical prediction schemes have been developed for natural frequency and centre of gravity height which require testing in further experiments.

8. DISCUSSION

The frequency with which seasons of widespread lodging occur shows no sign of diminishing. Indeed, 1997 was a severe lodging year and 1998 has seen crops lodge earlier than ever and promises to be one of the worst lodging years on record. This is despite the existence of several guidelines for reducing lodging (e.g. ADAS, 1996; BASF, 1995), despite 80% of the winter wheat crop consisting of varieties with high standing power scores of 7 or more out of 9, and despite PGRs being applied to 75% of the winter wheat crop at a cost of £11 million (Garthwaite *et al.*, 1996). This work shows that the main causes of the problem are:

- Cropping strategies at the time of sowing which fail to take sufficient account of lodging leading to the production of lodging prone crops.
- Failure to identify which spring crops are most lodging prone and why, leading to inappropriate targeting of lodging controls.

These problems originate from a poor understanding of the lodging process. Lodging is commonly perceived to be largely unpredictable, being caused by uncontrollable weather conditions during grain filling, resulting in buckling of the stem base. This perception has been proven to be a gross over-simplification by the development within this project of a model of the lodging process which accounts for weather, soil and plant factors. Lodging due to failure of the root anchorage system is apparently more common than stem lodging. Variation in the crop structure, as manipulated by husbandry, has been shown to be at least as important as the prevailing weather for influencing lodging. Finally, spring plant characters have been identified which may be used to predict the risk of stem and root lodging at a time when remedial controls can be applied. As a result of these findings lodging can be lessened through breeding varieties with better standing power, intelligent cropping strategy for producing sturdy crops and more effective control tactics based on spring assessments of crop growth.

8.1 MINIMISING LODGING

8.1.1 Lodging resistant varieties

Of the plant characters which influence stem and root lodging the most influential have been identified (Chapter 4). The leverage of the plant's aerial parts is influenced by the main shoot's height at centre of gravity and natural frequency together with the plant's shoot number. The plant's anchorage strength is influenced by the spread of the root plate and depth to which the structural (lignified) roots extend. The strength of the stem base is influenced by the stem radius, stem wall width and material strength of the stem wall. Plant breeders may use these to choose lodging resistant varieties more efficiently. Previously, breeders have minimised lodging susceptibility by selecting short varieties, with a small leverage force. Anchorage and stem strength properties have generally been neglected in the selection process. This study has demonstrated that there is large genotypic variation for the plant characters indicative of anchorage strength and stem strength (Chapter 6). This investigation was on relatively few varieties which suggests there could be even greater genetic variation from which varieties with strong anchorage and strong stems can be selected.

It is anticipated that techniques can be developed to allow these lodging-associated plant characters to be measured quickly and easily, to help variety testers gain a better estimate of a plant's lodging susceptibility without relying on the occurrence of lodging. This will enable a precise guide to standing power to be developed more quickly for existing and new varieties. Furthermore, these measurements will identify whether individual varieties are more prone to stem or root lodging. This will allow growers to target the most appropriate lodging controls at each variety. Growers will be able to use the improved standing power guide to grow sturdy crops more effectively. This may be done by matching varieties with expected environmental conditions, e.g. sowing weakly anchored varieties on soils with weak shear strengths could be avoided, as could sowing weak stemmed varieties early or on fertile soils.

It will be the role of further work to establish the lodging-associated plant characters as varietal traits and to encourage plant breeders and the NIAB to incorporate them into variety selection and testing processes. Further work may also attempt to establish a similar set of traits for barley and oats. The first step would be to modify the lodging model to be applicable to barley and oats. This would probably entail minor modifications to account for differences in the canopy characteristics, e.g. the oat panicle. The mechanism of anchorage may also be different, e.g. the roots of barley may not be rigid enough to hold a cone of soil, instead they may bend or stretch to cause root lodging. If this were the case a new model of root lodging may need developing. Once this step has been completed the model inputs (which may have changed) would be measured in a range of varieties and crops grown with different husbandry to establish their range. Then a sensitivity analysis may be carried out to determine the most influential characteristics, which once established as heritable traits could be used by testers and breeders.

8.1.2 Growing sturdy crops

Strategies for growing lodging resistant crops are poorly developed. Most consideration is given to site history and varietal standing power. Lodging has a low priority when the grower makes decisions about other husbandry factors, such as sowing date, seed rate and soil residual N.

This study has demonstrated that plant characters associated with lodging can be stretched more by husbandry decisions than by choice of variety. Given the large range in standing powers of the varieties tested, this highlights the potential for reducing lodging risk through crop management decisions, and strongly suggests that devising a cropping strategy for growing sturdy crops will be invaluable.

A guide to how husbandry factors affect lodging is described in Chapter 6. Variation in sowing date, seed rate and soil residual N affect the risks of stem and root lodging by different mechanisms. This knowledge will help growers choose cropping strategies which pre-empt potential causes of lodging, e.g. crops could be sown later to counter potential weak stem bases of crops sown on fertile soil, or seed rates could be cut to counter potential poor anchorage due to weak soil strength. The experiments have shown these types of early decisions to be very effective and inexpensive methods of lodging prevention.

One might expect the production of sturdy crops to compromise grain yield due to later sowing, the use of reduced seed rates and smaller nitrogen applications. This need not be the case. This study has shown that the golden rules for avoiding high lodging risk crops are to avoid spring crops with dense plant populations and large canopies. It should be possible to grow crops with a high yield potential without producing these undesirable spring crop characteristics. For example a crop may be sown early to generate a high yield potential, but the large spring canopy associated with early sowing could be limited by sowing less seeds and applying nitrogen later in the spring. Experiments in this project have demonstrated that seed rates can be reduced and the application of nitrogen delayed without reducing grain yield.

This study has shown that lodging risk can be reduced most effectively by taking the correct decisions at sowing. Remedial controls in spring were less effective at reducing lodging risk. In most cases spring remedial action certainly delayed lodging and often made the difference between a crop lodging or not lodging. However, in poorly managed crops spring remedial controls did not reduce lodging risk enough to prevent lodging. Thus the importance of developing strategies for producing lodging resistant crops is again emphasised.

Variation in the soil properties, texture and macroporosity (visual structure) were identified as very important in root lodging (Chapter 4). The grower cannot change texture, but may choose to alter cropping strategy to reduce lodging risk on soils textures which are most prone to lodging. This study observed that silt soils experienced the greatest lodging. This might have been due to their weak soil strength which would confer poor anchorage, or high fertility which might confer an excessive leverage force. Macroporosity may be a candidate for manipulation. Compacted soils with few macro pores are stronger and less prone to root lodging than friable soils with many macropores. It is likely that the tramline effect reported in Chapter 2 illustrates the effect for compacted soils to reduce lodging risk. The parametric analysis of the lodging model described in Chapter 4 indicates that other factors thought to cause the tramline effect such as sturdier plants due to lower seed rate or mechanical bruising seem less likely. Friable soils may be a result of soil type, autumn cultivations or frost heave. Rolling after drilling and in the winter or spring, if the state of the soil allows, is likely to increase soil strength by reducing its friability. When rolling, care would be required to avoid overcompacting the soil which would inhibit root growth. Also rolling after the beginning of stem extension should be avoided as it is likely to damage the extending apical tissues. More work is required to pin down the most effective methods for reducing friability and increasing soil strength, without adversely affecting crop growth.

8.1.3 Controlling lodging risk

The key to controlling lodging lies in accurately predicting which crops are at greatest risk to stem or root lodging. This study has proven that assessments of spring crops can be used to predict the risk of stem and root lodging. Furthermore, the spring crop characters indicative of lodging have been identified in Chapter 7. The spring indicators include plant number m^{-2}, shoot number m^{-2}, canopy size (GAI), soil N supply, leaf number per main stem and the thermal duration for successive leaves to emerge (phyllochron). Schemes have been developed linking these spring indicators with the summer-time values of the lodging model inputs, which will enable an assessment of lodging risk to be gained in the spring.

The schemes for assessing lodging risk in the spring require more development and testing in a wider range of sites and crops before they can be regarded as reliable enough to be quantitative. These assessments will provide the grower with information about which crops are lodging prone and why, by describing the crops potential leverage, stem strength and anchorage. This information alone will help remedial controls to be accurately targeted by pinpointing which crops require lodging controls and which crops require more than others. This will probably result in better lodging control for the same spend on PGRs, since crops at low lodging risk should receive less PGRs than previously, but high risk crops more.

The full benefits of these prediction schemes will only be realised when we acquire information about the mechanism and the quantity by which lodging controls, such as PGRs, reduced and delayed N applications and rolling, reduce lodging risk. It is envisaged that the grower can use this information in conjunction with the lodging model to decide upon the most appropriate method of lodging control for different crops. For example, a potentially poorly anchored crop might benefit most from spring rolling to strengthen the soil or a PGR application during tillering to stimulate root growth. A potentially weak stemmed crop might benefit most from small spring nitrogen applications to reduce canopy size or a PGR application during early stem extension to strengthen the stem bases. Armed with information about how lodging controls work the lodging model can weigh up their effect on a crop to allow the most effective one to be chosen.

This study investigated the effect of two PGRs and reduced N applications for reducing lodging risk. 5C Cycocel reduced the shoot leverage on average by 22%, 5C Cycocel followed by Terpal reduced shoot leverage by 30%. These PGRs had little or no effect on the stem or anchorage strengths. Reducing N applications through Canopy Management reduced the plant leverage force on average by 24%, shoot leverage force by 13% and on the most fertile sites increased stem strength on average by 24%. This type of information will provide the start point for helping the lodging model to calculate the best form of lodging control in different situations. However, these figures must be verified on a wider range of field sites and the effects of a range of other lodging controls must be investigated and quantified. Other PGRs to investigate include Moddus, Meteor, Cerone and Upgrade; other lodging controls include different rates and timings of N applications and autumn/winter/spring rolling. These investigations should yield ways of combating lodging risk in any situation.

Advice based on the lodging prediction scheme must be tentatively given during the early stages of its development and testing period. However, when it is considered that the majority of growers are not certain about how lodging occurs, even very general information such as whether or not a crop is likely to root or stem lodge will be valuable. As the parts of the prediction scheme are tested and improved the error should decrease to allow more refined advice to be given, such as PGR rates and timings.

This work opens up the opportunity for treating parts of fields differently. It was shown in Chapter 2 that almost all lodged fields had lodging in the boundary between the field margin and field centre, which was probably due to overlapping drilling and N applications. It was apparent that this lodging often precipitated lodging in the field centre. Therefore in the first instance growers must aim to avoid overlapping field operations. However, this may be impractical depending on the field shape and the size and precision of farm machinery. Spring crop assessments could be used to assess the risk lodging in the overlapping region as well as the field centre, thus giving growers the option of treating field overlaps separately.

The most commonly used PGRs, which were investigated in this study, reduced lodging risk by reducing crop leverage. However, this study has shown that the aerial forces imposed by the canopy on the plant base are less important in determining lodging than variation in the two points of plant failure. This may explain the poor lodging control which is sometimes found after the application of PGRs. An effective lodging control chemical must not only reduce leverage, but must also strengthen anchorage and the stem base. Some PGR manufacturers already claim these properties in their products, but this is not always supported by the scientific literature (Crook and Ennos, 1995). It is possible that these products do not always influence the plant characters associated with stem strength and anchorage strength. For example, a claim for increased 'rooting' does not necessarily mean the structural roots and anchorage are being maximised because it may refer to an improvement in the distal non-structural parts of the root system. Thus, chemical manufacturers must aim to manipulate the important lodging-associated plant characters, particularly the spread and depth of the root plate. That this can be achieved is demonstrated by the seed treatment 'Baytan', which increases crown depth by shortening the sub-crown internode (Montfort *et al.*, 1996).

8.2 CONCLUSIONS

The major success of this project has been the development of the first model of the lodging process which accounts for all influencing factors, including aspects of the weather, soil and crop. This is achieved by calculating the leverage force of the canopy, stem strength and anchorage strength. This model successfully accounted for variation in lodging of differently managed wheat crops. However, the calculation of soil shear strength must be further developed and more widespread validation is required to provide confidence in its output before it can be generally applied.

This model has helped fulfil one of the projects main objectives of investigating and quantifying the influence on lodging of rainfall, wind, field altitude, soil texture, soil structure, soil fertility, genotype, sowing date, seed rate, N applications, PGRs and stem base diseases. Crucially, factors which are under the growers control have been shown to influence lodging as strongly as uncontrollable factors such as the weather and soil texture, thus supporting the hypothesis that lodging can be predicted and therefore effectively controlled.

The plant characters which determine lodging risk have been identified by this study. This has opened a route for developing an accurate varietal standing power guide based on plant attributes rather than on the unreliable occurrence of lodging. These lodging-associated characters may also be utilised by wheat breeders to improve the efficiency with which they select for strong standing varieties. The next steps are to confirm these plant characters as heritable traits in winter wheat and to repeat a similar study for other lodging prone cereals, namely barley and oats.

The model of lodging has another use, that of predicting lodging risk in the spring when remedial controls can be applied. This study has completed its second main objective and proven that spring crop assessments can be used to predict lodging risk. Furthermore, spring indicators of lodging have been identified and prediction schemes have been developed. Further work is now required to test these and prove their value to growers. The greatest benefits of this prediction scheme will only be delivered with a strong understanding of how lodging controls reduce lodging risk. This study has begun this process, but more research is required on the wide range of potential lodging controls, particularly the newer plant growth regulator molecules and formulations.

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APPENDIX 1

ADAS CROP CENTRES
Winter Wheat Plant Growth Regulators - Risk Assessment Chart

Use this chart to estimate lodging risk and appropriate treatments based on ADAS trials or adjust husbandry to minimise lodging risk:

Assessment Factor	Score	Insert Your Individual Field Scores								
		1	2	3	4	5	6	7	8	9
SITE LODGING HISTORY										
None	+1									
Slight	0									
Some in most years	-1									
Severe in most years	-3									
DRILLING DATE										
Early September	-3									
Mid September	-2									
Late September	-1									
Early-mid October	0									
Mid October - Mid November	+1									
After Mid November	+2									
VARIETY										
Insert NIAB standing power score										
SPRING PLANT POPULATION										
< 200 per square m	+1									
200 - 250	0									
250 - 350	-1									
>350	-2									
YIELD POTENTIAL										
Less than 7t./ha	+1									
7 - 8	0									
8 - 10	-1									
More than 10	-2									
POTENTIAL MARKET										
Feed	0									
Bread or Seed	-1									
NITROGEN RATE AND TIMING										
If using ADAS recommended N rates but later than ADAS timings	+1									
ADAS recommended rate and timing	0									
40kg/ha N above optimum before GS 30	-2									
40 kg/ha N above optimum after GS 30	-1									
More than 40kg/ha N above optimum @ GS 30/31	-2									
40 kg/ha above optimum after GS 32	0									
Soils with unknown N residue	-1									
Using ADAS Soil Mineral N Service	0									

ACTION:
Please note that the following programmes will not provide lodging prevention where weather conditions are exceptionally conducive to lodging.

Final Score:

>7	Low risk - No need for PGR to reduce lodging
5-7	Medium risk - single PGR application
3-4	High risk - PGR sequences recommended
1-2	Very high risk - PGR sequences recommended, including split applications
0	Review cropping strategy to reduce lodging

APPENDIX 2.

Site records

1993-94

	1993-94
Field name	Dormington
Field altitude (m)	-
Soil texture & series	Bromyard - stoneless silty clay loam
Drainage	Well drained
Soil analysis pH	6.9
P, K, Mg : mg/l (Index)	42 (3), 176 (2), 73 (2)
Organic matter %	4.2
Previous cropping	Winter oats
Residual nitrogen kgN/ha	0 or 80
Cultivation's Time of sowing 1 & 2	Ploughed 14-Oct SKH crumbler x2 power harrow x1
Drilling date	Tos 1 16-Oct Tos 2 8-Nov
Drill type & width	Accord drill, 4.24m width
Seed rate	250s/m^2 500s/m^2
Row width	12 cm
50% Emergence date	Tos 1 18-Nov Tos 2 14-Dec
Crop protection Molluscicides	Draza 5.5 kg/ha 18-Nov
Herbicides	Glyphogan 3.0 l/ha 01-Oct Panther 2.0 l/ha 31-Jan
Fungicides	Tern + Sportak 45 28-Apr (0.75 l/ha + 0.9 l/ha) Impact Excel 19-May (2.0 l/ha) Tilt + Benlate 14-Jun (0.3 l/ha + 0.3 kg/ha)
Insecticides	Aphox 280 g/ha 30-Jun
Harvest date	17-Aug-94

1994-95

Experiment	1994-95
Field name	Belmont
Field altitude (m)	84
Soil texture & series	Bromyard - stoneless silty clay loam Middleton - stoneless silty loam
Drainage	Bromyard - well drained Middleton - seasonal waterlogging
Soil analysis pH	7.4
P, K, Mg : mg/l (Index)	32 (3), 242 (2), 117 (3)
Organic matter %	2.8
Previous cropping	1993 Spring Oilseed rape 1992 Spring Barley / Spring Oats 1991 Winter wheat
Cultivations **Early sowing** **Late sowing**	Ploughed 12/9/94 Power harrow x1 23/9/94 SKH crumbler x2, power harrow x1 17/10/94
Drilling date	Early sowing 23/9/94 Late sowing 17/10/94
Drill type & width	Accord drill, 4 m width
Seed rate	500 seeds m^{-2}=201.1 kg ha^{-1} 250 seeds m^{-2}=100.6 kg ha^{-1}
TGW of seed (g)	39.98
Row width	12 cm
50% Emergence date	Early sowing 3/10/94 Late sowing 3/11/94
Herbicides	Javelin Gold (5.0 l ha^{-1}) 16/11/94
Fungicides	Tern + Sportak 45 (0.75 l ha^{-1}) + (0.9 l ha^{-1}) 13/4/95 Corbel CL (2.5 l ha^{-1}) 18/5/95 Legend + DerosalWDG (0.7 l ha^{-1}) + (0.2kg ha^{-1}) 9/6/95
Insecticides	Decis (200ml ha^{-1})16/11/94 Phantom (100g ha^{-1}) 28/6/95
Harvest date	11/8/95

1995-96

Experiment	**1995-96**
Field name	Jubilee
Field altitude (m)	84
Soil texture & series	Bromyard - stoneless silty clay loam
Drainage	Bromyard - well drained
Soil analysis pH	7.1
P, K, Mg : mg/l (Index)	74 (5), 428 (4), 125 (3)
Organic matter %	2.9
Previous cropping	1994 Winter oilseed rape 1993 Winter wheat/ winter barley 1992 Winter wheat
Cultivations **Early sowing** **Late sowing**	Ploughed 18/9/95 Power harrow x1 20/9/95 Power harrow x1 01/11/95
Drilling date	Early sowing 20/9/95 Late sowing 01/11/95
Drill type & width	Accord drill, 4 m width
Seed rate	500 seeds m^{-2} = 233.0 kg ha^{-1} 250 seeds m^{-2} = 116.5 kg ha^{-1}
TGW of seed (g)	46.60
Row width	12 cm
50% Emergence date	Early sowing 01/10/95 Late sowing 22/11/95
Herbicides	Javelin Gold 2.0 l ha^{-1} Isoproturon (1.0 l ha^{-1}) Ally (30 g/ha) 1/5/96 Cheetah (2.5 l ha^{-1}) Starane (0.5 l ha^{-1}) 9/5/96
Fungicides	Sportak 45 (0.9 l ha^{-1}) Tern/Patrol (0.75 l ha^{-1}) 1/5/96 Folicur (1.0 l ha^{-1}) 30/5/96 Silvacur (1.0 l ha^{-1}) Patrol (0.5 l ha^{-1}) 22/6/96
Insecticides	Draza (5.5 kg ha^{-1}) 19/10/95 Metarex (7.7 kg ha^{-1}) 3/11/95 Cypermthrin (0.25 l ha^{-1}) 1/3/96
Harvest date	19/8/96

Nitrogen fertiliser applications (kg ha^{-1} N) and timings for all 'normal nitrogen' treatments.

Treatment	split	1993-94	1994-95	1995-96
Early sown +	Early split	80 (21/3/94)	30 (8/3/95)	40 (14/3/95)
High residual N	Late split	120 (25/4/94)	120 (4/4/95)	110 (4/4/95)
Early sown +	Early split	80 (21/3/94)	30 (8/3/95)	40 (14/3/95)
Low residual N	Late split	120 (25/4/94)	170 (4/4/95)	160 (4/4/95)
Late sown +	Early split	80 (6/4/94)	30 (8/3/95)	40 (14/3/95)
High residual N	Late split	120 (25/4/94)	110 (13/4/95)	100 (29/4/95)
Late sown +	Early split	80 (6/4/94)	30 (8/3/95)	40 (14/3/95)
Low residual N	Late split	120 (25/4/94)	160 (13/4/95)	150 (29/4/95)

Nitrogen fertiliser applications (kg ha^{-1} N) and timings for the 'Canopy Management' lodging control treatments.

Treatment	split	1993-94	1994-95	1995-96
Early sown +	1st split	30 (21/3/94)	-	-
High residual N	2nd split	-	-	-
	3rd split	-	50 (5/5/95)	-
	late split	60 (20/6/94)	60 (12/6/95)	-
Early sown +	1st split	30 (21/3/94)	80 (4/4/95)	-
Low residual N	2nd split	-	-	50 (2/4/96)
	3rd split	-	-	-
	late split	60 (20/6/94)	60 (12/6/95)	-
Late sown +	1st split	30 (6/4/94)	30 (13/4/95)	-
High residual N	2nd split	-	20 (5/5/95)	-
	3rd split	-	-	-
	late split	60 (20/6/94)	60 (12/6/95)	-
Late sown +	1st split	30 (6/4/94)	30 (13/4/95)	30 (11/3/96)
Low residual N	2nd split	-	50 (26/4/95)	60 (17/4/96)
	3rd split	-	-	40 (8/5/96)
	late split	60 (20/6/94)	60 (12/6/95)	-

Timings of PGR treatments for all experiments

Treatment	PGR	1993-94	1994-95	1995-96
Early sown	5C Cycocel (2.5 lha^{-1})	3/5/94	24/3/95	3/4/96
	Terpal (1.5 lha^{-1})	19/5/94	20/5/95	2/6/96
Late sown	5C Cycocel (2.5 lha^{-1})	3/5/94	10/4/95	25/4/96
	Terpal (1.5 lha^{-1})	19/5/94	20/5/95	7/6/96

APPENDIX 3.

Lodging model Notation

a	stem base radius
A	ear area
B	wind induced base bending moment
B_R	root failure moment
B_S	stem failure moment
c	clay content
c_R	reference value of c
C_D	drag coefficient
d	root plate diameter
f	water content at field capacity (by weight)
g	acceleration due to gravity
g_v	velocity gust factor
h	site altitude
i	daily mean rainfall
i_{50}	daily mean rainfall exceeded 50% of the time
I	second moment of area of stem base
J_1	function in equation (20)
J_2	function in equation (21)
k_1	constant in wind Weibul distribution
k_2	constant in wind Weibul distribution
k_3	constant in rainfall distribution
k_4	constant in equation (11)
k_5	constant in equation (24)
l	structural rooting depth
L	function in equation (18)
${}^{x}L_V$	turbulence length scale
n	natural frequency
n_D	natural frequency in dry soil conditions
n_W	natural frequency in wet soil conditions
N	number of shoots per plant
p_r	probability of daily mean rainfall exceeding i
p_R	probability of root lodging
p_{RS}	probability of stem and root lodging
p_S	probability of stem lodging
p_T	total lodging probability
p_W	probability of daily maximum hourly mean wind speeds exceeding V
P_T	lodging probability in one season
s	soil shear strength
s_D	s at permanent wilting point
s_W	s at field capacity
t	stem wall thickness
T	observation time
T_T	lodging return period
u_i	term in equation (28)
v	visual source

v_R	reference value of v
V	daily maximum hourly mean wind speed
V_g	gust wind speed
V_{50}	corrected value of V_{50}'
V_{99}	corrected value of V_{99}'
V_{50}'	hourly mean wind speed exceeded 50% of time
V_{99}'	hourly mean wind speed exceeded 1% of time
X	centre of gravity height of shoot
w	water content at permanent wilting point (by weight)
z_O	surface roughness length
δ	plant damping ratio
ρ	density of air
ρ_S	density of soil
ρ_W	density of water
σ	stem failure yield stress
σ_V	wind turbulence