UNDERSTANDING AND ASSESSING LODGING RISK IN WINTER WHEAT

by

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DEDICATION

This thesis is dedicated to Mum, Dad, Tim and Barney.

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GENERAL ABBREVIATIONS

ADAS = formerly Agricultural Development and Advisory Service, now ADAS Consulting Limited

av. = average

AWC = available water capacity

C = centigrade

cm = centimetre

cv. = cultivar

CV% = coefficient of variation

df = degrees of freedom

DESSAC = Decision Support System for Arable Crops

DM = dry matter

g = grams

GAI = green area index

GS = plant growth stage (Zadok's)

h = hours

ha = hectares

HFN = Hagberg falling number

HGCA = Home-Grown Cereals Authority

HI = harvest index

Hz = hertz

kg = kilograms

km = kilometres

kPa = kilopascals

l = litres

LTM = long term mean

LSD = least significant difference

m = metres

MAFF = Ministry of Agriculture, Fisheries and Food

MC = moisture content

min = minutes

mm = millimetre

MPa = megapascals

N = nitrogen

NIAB = National Institute of Agricultural Botany

Nm = newton metres

No. = number

OM = organic matter

p = probability value

PGR = plant growth regulator

RL = root lodging

s = second

SEM = standard error of the mean

SL = stem lodging

SMD = soil moisture deficit

SMN = soil mineral nitrogen

SPWT = specific weight

t = tonnes

TDR = time-domain reflectometry

TGW = thousand grain weight

UK = United Kingdom

vs. = versus

° = degrees

EXPERIMENTAL SITE & TREATMENT CODES

TOS 1 = first time of sowing (early)

TOS 2 = second time of sowing (late)

HSR = high seed rate

LSR = low seed rate

330-ResN = high residual nitrogen level

30-ResN = low residual nitrogen level

NIL = nil 'lodging control'

5C = '5C Cycocel' chlormequat

5C+T = '5C Cycocel' chlormequat plus 'Terpal'

G5 = nitrogen 'canopy management'

Treatment combinations

TOS 1 = **1** or TOS 2 = **2**

HSR = **H** or LSR = **L**

330-ResN = **N** or 30-ResN = **O**

NIL = **1** or 5C = **2** or 5C+T = **3** or G5 = **4**

For example, **1HN1** = TOS 1, HSR, 330-ResN, NIL

2LO3 = TOS 2, LSR, 30-ResN, 5C+T

NB: where treatments are referred to in the text, tables or figures, they are always ordered as follows; the first number refers to sowing date, the first letter to seed rate, the second letter to residual nitrogen and the second number to lodging control.

Site codes

MT94 = main experiment site in the 1993-94 season.

ST94 = supplementary experiment site in the 1993-94 season.

MT95 = main experiment site in the 1994-95 season.

VT95 = variety trial site in the 1994-95 season.

MT96 = main experiment site in the 1995-96 season.

ENGINEERING MODEL CODES

Aerodynamics and Meteorological Parameters
V = velocity
Vg = gust velocity
V_{50} = mean hourly wind speed
V_{99} = extreme hourly wind speed
I_{50} = average daily rainfall
H = field altitude above sea level
c = damping ratio
C_D = drag coefficient
τ = wind loading time
T = observation time
g = acceleration due to gravity
ρ = air density
z_0 = surface roughness length

Canopy Parameters
n = plant natural frequency
n_0 = dry natural frequency
X = height at the centre of gravity
N = shoot number
A = ear area

Stem Base Parameters
B = base bending moment
B_S = stem failure moment
σ = stem failure yield stress
a = stem radius
w = stem wall width
E = Young's modulus of elasticity
I = cross-sectional second moment of area
EI = flexural rigidity

Root Parameters
B_R = root failure moment
D = average root cone diameter
l = structural rooting depth

Soil Parameters
s = soil shear strength
s_0 = dry soil shear strength
m = soil porosity

P_S = probability of stem lodging
P_R = probability of root lodging
P_T = total probability of lodging

ABSTRACT

A detailed literature review was done which indicated that there was still some 'uncertainty' as to the exact cause of lodging and also identified the need for a quantitative method to assess lodging risk. Separate published models for determining the windthrow of trees and the anchorage of wheat roots were combined, and a model was developed in order to integrate all aspects of lodging in wheat, and express them in terms of risk. The model was broadly sectioned into three components; the plant canopy, stem base, and roots. The aerial force imposed on the stem base and roots was calculated (using both plant measurements and randomly selected weather conditions in July). By comparing this to the failure moment of the stem base and roots, the model then predicted the probability of lodging occurring. At the same time, wheat was grown in a series of field experiments at ADAS Rosemaund, Herefordshire between 1994-1996 and the effects of various agronomic factors on the crop and its yield were found to be similar to those reported in previous work and from practical experience. Lodging was most prevalent during the 1995-96 season causing yield losses of up to 1.3 t/ha, while very little lodging occurred in the previous two seasons. Reductions in grain quality were also associated with lodging in both the 1994-95 and 1995-96 seasons. Lodging was observed to occur by both stem failure and root failure, with root failure being the predominant cause in 1996. Lodging was influenced most of all by 'crop structure', as affected by agronomy, which was clearly illustrated by 93% lodging occurring in the early-sown, high seed rate, high residual nitrogen treatment compared to only 8% lodging in the late-sown, low seed rate, low residual nitrogen treatment. It was found that the latter treatment described, with the addition of full PGR, had no lodging in any season, as a direct result of lodging resistance gained from optimising plant structure due to crop husbandry. The actual 'type' of lodging was also influenced by the state of the soil; in the dry summer of 1995, soil strength was very high (average c.100 kPa) and lodging occurred by stem failure, whereas during 1996 when root lodging occurred, the surface soil was moist and soil strength was much lower (average c.20 kPa). Agronomic practices greatly affected lodging risk in the field experiments. A low seed rate (250 seeds/m^2) provided the most consistent and effective method of reducing lodging in all seasons, by significantly increasing the stem diameter (by up to 0.35 mm) and improving root structure (by producing up to 7 more crown roots and increasing the size of the root cone diameter by up to 7 mm). Early sowing (late-September) increased crop height (by up to 6 cm) in all seasons except 1994-95 and resulted in increased lodging in the 1995-96 season. High soil residual nitrogen increased lodging slightly but its effect on 'crop structure' was much less than seed rate or sowing date in all seasons. Plant growth regulators (PGR) reduced lodging compared to the nil 'control' by significantly reducing stem height (average c.10cm), but not through increasing stem failure moment or thickening the stem wall width. The reduced nitrogen 'canopy management' treatment also generally reduced lodging across seasons compared to the nil 'control' although, not by as much as or as consistently as with PGRs. Two PGR-use schemes currently available were examined and recommendations given were found to be poor when compared to the experimental findings and much less 'comprehensive' than the modelling approach used here. Other results from a range of winter wheat varieties tested found that variation in basal stem structure and crown root structure was large, which was shown by the model to have implications in terms of lodging risk. These findings indicate the need for improved information and better targeting of varietal lodging resistance in the future. Other findings showed that the use of 'Baytan' seed treatment significantly decreased lodging risk by producing a deeper crown root anchorage and a larger root cone diameter. It was also found that severe stem base disease (fusarium and sharp eyespot) reduced the stem failure moment causing up to 40% greater lodging risk compared to uninfected stems. The model was then used to support the experimental findings by converting the large differences caused in plant structure into estimates of lodging risk and results showed that model probabilities matched reasonably well with the actual lodging in the various experimental treatments. Certain measurements such as plant height and angle of root spread were found to be unimportant. In contrast, a model sensitivity analysis found that plant natural frequency, stem base diameter and root cone diameter were crucial 'indicators' of lodging risk. It was also found that wind speed and field altitude were less influential than rainfall in increasing lodging risk. A hand-held lodging device (torquemeter) was field tested and provided important results which found the relationship assumed in the model between soil strength and root failure to be flawed, so that root lodging was underestimated. This finding has allowed considerable improvements to be made to the below-ground model. The identification of various 'indicators' of lodging risk have successfully provided the basis for further development of the model, to enable a more quantitative, predictive lodging risk assessment scheme for use by farmers and consultants.

1. INTRODUCTION

Better understanding, assessment and prediction of lodging risk is needed to increase the technical efficiency and profitability of UK cereal production. This chapter introduces briefly the problems of lodging to the cereal industry and, focusing on winter wheat, examines how farmers and agronomists perceive and understand lodging. It also looks at the contribution made by the plant breeding industry to reduce the lodging problem. Finally, it outlines the main aims and objectives of the thesis.

1.1 The problem

Lodging is an important problem in all cereals (wheat, barley and oats) but, this study looks solely at lodging in winter wheat (*Triticum aestivum*), see Plate 1.1 (Appendix 1). Wheat is the most important arable crop in the UK with an area of 1,963,000 ha grown in 1996/97 (HGCA, 1997a). Wheat production in the UK increased from 14.3 million tonnes in 1995/96 to 15.9 million tonnes in 1996/97, and average yields from 7.70 t/ha to 8.08 t/ha respectively (HGCA, 1997a). Lodging is still a serious problem for cereal growers in spite of varieties with improved lodging resistance and of the widespread use of plant growth regulators (PGRs). When extensive lodging occurs in seasons such as 1980, 1985, 1987 and 1992, costs to the industry are large through lower yields, delayed harvest, reduced combine speed, grain losses at harvest, poor grain quality and the need for greater grain drying (ADAS, unpublished). In 1992, plant growth regulator trials done at ADAS Rosemaund showed an average yield loss due to lodging of 0.4 t/ha (maximum 1.0 t/ha), with the level of yield loss depending on the severity of lodging and the growth stage at which lodging occurred. The most recent, severe lodging years were in 1992 and 1997. In 1992, when an estimated 16% of the UK wheat crop lodged (Scott *et al.*, 1998), yield losses between 0.5-2.0 t/ha (BASF, 1995a) would have cost UK wheat growers between £20-80 million, based on 1992-93 average prices of feed wheat. Lodging in 1992 also caused a considerable reduction in grain quality which is evident from the following HGCA statistics. Compared to a five-year UK average (1992-96), Hagberg Falling Number was reduced from 281 to 254 in 1992, the amount of small grains increased from

1.9% to 2.6% in 1992, specific weight decreased from 76.6 kg/hl to 73.4 kg/hl in 1992 and thousand grain weight was reduced from 45 g to 39 g in 1992 (HGCA, 1997a). These effects resulted in a smaller quantity of the wheat crop reaching breadmaking quality, thereby reducing growers' income further through the loss of milling premium. In 1997, it was estimated by BASF (Anon., 1998) that lodging cost UK cereal growers £110 million. This figure assumed 15% lodging in wheat and 30% lodging in barley, with reduced yield, missed quality premiums and additional harvesting and drying costs adding up to £197/ha and £200/ha respectively. Even in years without severe lodging, BASF (1995b) estimates that lodging in cereals costs over £11 million in lost grain every year in the UK, based on a lodging incidence of 10% and yield losses of 5-10%. If combining, cleaning and drying costs are taken into account, the total loss could be £30 million (BASF, 1995b).

Severe, widespread lodging occurs on average once every five years in the UK, and is often associated with very wet summers, such as in 1992 (Easson *et al.*, 1992) and 1997. In other years, less widespread lodging may occur more frequently on some farms or in certain fields which is probably related to some aspect of crop management practice and/or field topography. The cost of lodging control measures has been shown to be very high. In a MAFF survey on pesticide use (Woolley, 1992), the number of PGR applications was found to have doubled between 1982 and 1990. The estimated cost of PGRs applied to cereals in 1990 was £9.9 million, 70 % of which were applied to winter wheat. By 1994, 1,765,566 ha of wheat were treated with PGRs which represented 74% of the total wheat area grown in the UK (Garthwaite *et al.*, 1994). These applications are made routinely each year as an 'insurance' measure regardless of lodging risk. The application of chlormequat alone accounted for 86% of the total area of wheat treated with PGRs in 1994 (Garthwaite, *et al.* 1994). Yet in years when lodging was severe, even full commercial rates of PGR were not able to prevent lodging completely (Woolley, 1992). Hence, there is a need to understand better which factors affect lodging risk in order that control measures can be more accurately targeted and undertaken only when necessary.

1.2 Understanding 'lodging risk'

The concepts of understanding 'lodging risk' in winter wheat and of 'risk assessment', in order to reduce lodging for the benefit of the UK cereal industry, are central to this thesis. A better method of 'risk assessment' should lead to improved husbandry guidelines for winter wheat, informing the grower of the best ways of avoiding or reducing lodging. The latter could essentially form part of an 'integrated risk management scheme', made possible only after a more quantitative 'risk assessment' has been achieved. The above scheme may in the future be suitable for incorporating into a Decision Support System for winter wheat e.g DESSAC (Audsley *et al.*, 1997).

'Risk' can be defined as the uncertainty of a particular outcome. Various components of risk may be important in relation to the phenomenon of lodging:-

- ***The future*** cannot be predicted accurately and future events such as the weather (especially), plant disease infections and crop damage by animals will affect the crop.
- ***The knowledge*** we have of the way in which a crop grows and develops is incomplete. For example, we do not know everything that affects plant height, root structure etc., so these result in an element of unpredictability.
- ***The measurement/sampling techniques*** we use cannot measure causal factors (e.g. soil moisture, stem failure moment etc.) with absolute certainty. This is partly because present techniques are imperfect, and partly because the techniques for measuring crop attributes limit the size of samples we can measure.

Many aspects which may affect lodging risk will however be known to the grower before the crop is sown, such as the soil type, variety, seed bed structure, drainage and site lodging history (e.g. soil fertility and field topography). These 'field factors' are established features of the crop's environment. Other factors affecting lodging, such as weather conditions or disease infection, will only become apparent as the season progresses. Finally, many morphological characteristics which relate to lodging risk will only become apparent as the crop develops and grows, as illustrated in The Wheat Growth Guide (HGCA, 1997b). By assessment of these characteristics through the season, it may be possible to begin to predict the size and potential of the crop in advance which will help to determine the potential lodging risk, see Plate 1.2 (Appendix 1). It is the 'state' of the plant which is ultimately likely to be the most important factor determining whether lodging occurs.

Experience has led to 'common perceptions' by growers and the industry, that various factors will either increase or decrease the risk of lodging. The choice of variety is foremost in many growers' minds, with the NIAB 'Standing Power Rating' giving an indication of lodging (NIAB, 1998). Generally, varieties with low standing power are considered more likely to lodge. Other factors such as early sowing, high seed rates, high residual nitrogen levels and high fertiliser nitrogen applications for winter wheat all increase lodging risk but the reasons for this are not yet fully understood. PGRs shorten and strengthen stems, resulting in an improved resistance to lodging (Sylvester-Bradley & Scott, 1990). The effective control of stem base diseases is also important in reducing lodging risk (Griffin & King, 1985). High yielding soils, with good fertility (high organic matter content) are often more prone to lodging (D.B.Davies, *pers. comm.)*, whereas some soil cultivations such as rolling in the autumn and/or spring may improve the seedbed structure and help to prevent lodging (Crook, 1994). Other non-agronomic factors which influence lodging include the use of commercial products such as Baytan (fuberidazole + triadimenol) seed treatment. This is widely regarded as producing a growth regulatory effect which reduces lodging (Anon., 1993; Montfort *et al.*, 1996).

The following section is centred on the 'common perceptions' relating to lodging (outlined above) in an attempt to understand more fully the important components of lodging risk. It should be noted that the issues below will be examined in more detail in the review of literature in Chapter 2.

When choosing a variety, the grower needs to consider lodging-related attributes, but yield potential and market acceptability are clearly still the dominant factors.

Currently, the only two relevant attributes affecting lodging which are used in UK recommended variety lists are standing power and shortness of straw (NIAB, 1998). Standing power is scored on a 1-9 scale and is dependent on lodging scores recorded within NIAB trials. Varieties with ratings of 8 or 9 are described as 'very stiff strawed' and will usually lodge only under the most adverse conditions, whereas varieties with 6 or 7 ratings also have stiff straw but may lodge in certain seasons or on very fertile sites (Fenwick, 1995). Shortness of straw (also scored on a 1-9 scale) may be greatly influenced by growing conditions, with a one point increase on the scale representing a 5 cm decrease in length of straw.

Experience has shown that early sowing increases stem length and canopy size in wheat which often leads to more stem lodging (Kirby *et al.*, 1985; Fielder, 1988).

Seed rate is flexible and is a very important consideration in terms of lodging risk. A high plant population density is more likely to increase lodging (Easson *et al.*, 1993) because competition for space, light and nutrients amongst plants leads to longer and weaker stems. The latter are also more prone to the effects of disease, especially eyespot.

High applications of inorganic nitrogen fertiliser and/or high residual levels of organic nitrogen will produce tall, lush crops with weaker stems (Plate 1.2), therefore increasing the risk of lodging (Graham, 1983; Easson *et al.*, 1992; Crook, 1994). Hence, the positive effects of nitrogen in terms of yield potential may produce a crop very prone to lodging, either directly or indirectly due to disease infection. Highly fertile soils (e.g. peat soils, and areas such as 'meadowland' and 'valley bottoms') can also increase lodging risk, probably through increasing canopy size.

The most important diseases which can influence lodging are common eyespot (*Pseudocercosporella herpotrichoides*), sharp eyespot (*Rhizoctonia cerealis*) and fusarium foot rot (*Fusarium spp.*) . Varieties vary in their resistance to common eyespot and no fungicide will give total control of the disease at present (Griffin & King, 1985; Jones, 1994). Severe attacks of eyespot can greatly increase lodging risk

(ADAS, 1985) and eyespot lesions can cause yield loss when there is substantial girdling of the stem, particularly if the stem is softened and predisposed to lodging (Jones, 1994). In 1987, eyespot was the most serious disease in winter wheat with average yield losses of 0.58 t/ha nationally, which cost the industry £29 million (Sylvester-Bradley & Scott, 1990). Mean annual losses in the UK due to eyespot between 1985-1989 were £26.3 million, and the only pathogen to cause greater losses during this period was *Septoria tritici* (£34.5 million), (Jones, 1994).

The effect of PGR applications modifying plant growth and developmental processes is well documented (Caldicott & Lindley, 1964; Bragg *et al.*, 1984; Green, 1986; Woolley, 1980; 1992; Woolley *et al.*, 1991). Work by these authors has shown that PGR effects include delaying the start of stem extension (GS 30), reducing internode lengths and increasing stem wall thickness, all resulting in improved crop resistance to lodging.

Weather is one of the most important aspects affecting lodging. The lodging event tends to be associated with strong winds and heavy rainfall, such as the severe lodging in 1992 after a very wet summer (Easson *et al.*, 1993). The exact mechanism and type of failure is less well understood and subject to debate. However, it is generally perceived at present by growers that strong wind gusts (and to a lesser extent rainfall) may cause stem lodging directly, by exerting force onto stems which will fail at a critical point (Pinthus, 1973; Neenan & Spencer-Smith, 1975). Geographical position is also important, with a greater prevalence of lodging in the west and the north.

Finally, lodging commonly occurs in the field headlands first, and where severe lodging occurs, crops often remain standing along the field tramlines (Plate 1.1), giving rise to what is commonly known as the 'tramline effect'.

Where the results from the field experiments or lodging model are discussed in later chapters, the term "as expected" will apply when they agree with the 'common experience' outlined above.

1.3 Progress through plant breeding

In recent years, improved understanding of the growth and development of winter wheat has aided the breeding of better varieties and improved the definition of the wheat ideotype for modern agricultural conditions (Donald, 1968; Austin *et al.*, 1980). Modern varieties tend to have more erect canopies which are more efficient at intercepting light, resulting in better growth of ears and ultimately in increased yield and a higher harvest index. The increase in harvest index has also been associated with the search for shorter, stiffer stems to withstand lodging and, when such crops lodge, grain filling is generally restricted more than stem growth producing a lower harvest index (Sylvester-Bradley & Scott, 1990). It seems likely that there will in future be a limit to the extent to which improvements in harvest index and interception and conversion of photosynthetically active radiation (PAR) can be relied on in the breeding of varieties for increased grain yields (Sylvester-Bradley & Scott, 1990). Genes chosen by plant breeders to reduce stature as a means of minimising yield losses due to lodging must be capable of producing shorter plants with no reduction in grain yield (Lupton, 1987). The Norin 10 genes R*ht1* and R*ht2*, which operate by reducing stem internode length while having no direct effects on spike morphology were a means of achieving this. Their value is reflected in the part that Norin 10-derived semi-dwarf varieties have played in the world-wide increases in wheat yields since the 1960s (Lupton, 1987).

1.4 Main aims and objectives

Current guidelines for lodging risk in winter wheat are rather limited, such as NIAB Varietal Standing Powers (NIAB, 1998) and various schemes to guide PGR use such as the BASF 3-Step PGR Decision Guide (BASF, 1995a). Apart from guidelines such as these, lodging control is often based around local practice, farmers' experience and intuition rather than comprehension. For these reasons, much conjecture still exists about how best to prevent lodging. It is the aim of this HGCA funded 'Lodging Project' to test the belief that crop inspections in spring, together with other intelligence, can be used to significantly improve a) the assessment of lodging risk and b), the identification of effective controls.

It is important to recognise that work described in this thesis has addressed the model of Baker (1995) in two distinct ways. Firstly, the model has been used as a tool to further understand the mechanism of lodging and elucidate the influence of environmental and agronomic factors on the process. The model is therefore an integral and essential component of our overall intention to refine current advice according to observations and predictions of crop progress. Secondly, the work has helped to further develop our understanding of lodging in winter wheat by 'calibrating' the model at the time of lodging in the summer.

The development of an effective prediction system for lodging risk in winter wheat would be of great benefit to the cereal industry. Hopefully, this will ultimately allow us to predict lodging risk with confidence by developing a useable method of identifying individual crops at high risk, and then controlling lodging at least cost. Conversely, crops at low risk of lodging could be identified and expenditure on PGRs and other control measures avoided.

The main aims of this thesis are :-

- to understand further the lodging process by identifying the key determinants of lodging risk, and allow more effective targeting of those crops for which some change in management is needed, see Plate 1.3 (Appendix 1);
- to increase the awareness of why and how lodging occurs;
- to compare the current schemes available to growers, such as NIAB varietal standing powers and PGR-use ratings, against findings from the model, in order to find any misconceptions about the critical components of lodging risk;
- to produce improved agronomic guidelines to inform growers of the best ways to avoid lodging and to indicate where lodging control needs to be fully targeted (which may provide future guidance for plant breeders);

- to move towards minimising lodging in the national crop by considering the initial results of a more quantitative assessment of lodging risk through the use of the model developed by Baker (1995).

1.5 Structure of thesis

Chapter 2 examines the scientific literature on lodging in winter wheat. The main principles of lodging risk are reviewed to determine the current state of knowledge as to the causes of lodging and the types of lodging which exist. This chapter reveals misconceptions in the industry and areas of uncertainty as to how lodging occurs. It also highlights the need for a more quantitative assessment of lodging risk. The latter is addressed in Chapter 3 where an engineering approach towards the lodging problem is described. Engineering skills were used to design a relatively simple model of the complex wheat lodging process which could be used to predict lodging risk. This model process takes into account the agronomic perceptions of lodging gained from the literature. These give an insight into the critical parameters involved in lodging risk on which the model is based. The different components of the model are considered in detail and the calculation of the probability of lodging risk is explained.

With this background, Chapter 4.1 describes the experiments which were set up to provide a testbed for examining lodging risk. The main experiment was designed with prior knowledge (from established 'groundtruth') of the factors within our control that enabled the lodging risk system to be fully stretched. It encompassed the elements of crop husbandry which we know to be critical in determining lodging risk. For example, agronomic factors such as seed rate, sowing date and nitrogen were varied to produce crops with low and high lodging risks. Manipulating these agronomic factors changes the way in which the crop grows and develops which will, in turn, alter the important model parameters set out in Chapter 4.2. Various model specific measurements are described in Chapter 4.2, all of which, based on an initial sensitivity analysis of the model, were thought to influence lodging risk.

The effects of the agronomic factors on selected model specific measurements (outlined in Chapter 4.2) were analysed and are presented in Chapter 5. In addition, Chapter 5 also provides a brief description of crop establishment, growth and yields in relation to seasonal weather data for each experimental year, to give a wider perspective to the measurements.
Since little lodging occurred in the field experiments, the model specific data analysed in Chapter 5 were then entered into the lodging risk model, and the results presented in Chapter 6 to show how the different agronomic treatments altered lodging risk. The model, therefore, acts as a useful tool to test both farmers' perceptions and the impressions from the literature of determination of lodging risk. Chapter 6 also compares predicted model risks with NIAB varietal standing powers, PGR-use schemes and claims made for the effectiveness of specific plant growth regulators currently on the market.

Chapter 7 discusses the implications of the results from Chapters 5 & 6. Conclusions are then drawn in relation to the main aims and objectives set out in this Chapter. Finally, areas of further work and the implications for 'technology transfer' are considered.

2. LITERATURE REVIEW

2.1 The cause of lodging : root or stem ?

There is a question as to whether lodging originates from a failure in the soil, root, stem, or in a combination of these. Currently, most growers and agronomists consider that stem buckling is the cause of lodging. However, heavy and/or prolonged rainfall may also lead to root failure, due to wet soil decreasing the soil strength to a point where structural roots lose anchorage in the soil, causing root lodging under little or no wind (Pinthus, 1973; Graham, 1983). It is most likely that both types of lodging exist and are dependent on the seasonal weather, soil type and perhaps more importantly, the state of the crop itself. Sylvester-Bradley & Scott (1990) stated that many interrelated attributes within soil, root and stem complexes may cause a particular crop to lodge or remain upright, such as:

- surface layer soil strength (highly dependent on moisture content and texture);
- crown rooting pattern and structural integrity;
- crown depth which depends on sowing depth and seed treatment (e.g. Baytan);
- stem thickness and strength, particularly of the lower internodes;
- stem length and weight distribution which affect the moment on the stem base;
- crop canopy structure which affects air movement and rain-trapping;
- wind speeds and rainfall which depend on weather and field exposure.

The 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 the soil. Pinthus described stem lodging as the bending or breaking of the lower stem internodes and found that it was restricted to plants held tightly by a dry and thus hard upper soil layer. Root lodging was defined as straight and intact stems leaning from the crown, involving some disturbance of the root system. Pinthus showed that in moist soil the roots and crowns will give way to the torque or turning moment created by the wind. Root lodging was often associated with the development of cracks in the soil on the opposite side of the plant to the lodging.

In contrast to Pinthus, Neenan & Spencer-Smith (1975) argued that structural failure in wheat occurred by buckling rather than loss of anchorage. A theoretical study established the relationship between a lateral force applied to the ear and failure of the straw (determined by Young's modulus and stem diameter). Wind tunnel experiments were carried out and established that wind speeds of 22 m/s were necessary to cause stem failure in the field. Most of their data were generated from whole plant bending tests performed in the laboratory where crown roots were not anchored in soil cores. The main strength of their evidence was based on findings which showed that root strength and root number during July were sufficient to prevent root lodging, and they stated that shearing of the soil, such as occurs in the windthrow of trees, would not occur in cereals. However, Neenan & Spencer-Smith also stated that, in some cases, root degeneration at the end of the season could possibly cause lodging.

Graham (1983) broadly agreed with Pinthus (1973) that lodging was caused mainly by loss of anchorage as a result of failure of the root-soil interface, rather than by stem breakage or buckling. Graham carried out experimental work on all aspects of stem structural properties in relation to lodging resistance, including wind tunnel studies, and found no satisfactory explanation for the physical reasons for lodging above-ground. Graham also considered that the theoretical wind speeds necessary to cause stem failure were much greater than those experienced in the field. He then empirically examined the mechanical relationships in surface soil and the root-soil interface, and concluded that mechanical strength is often sufficiently reduced enough in wetted soil to cause below-ground failure. Also of importance, Graham concluded that the morphological crop characteristics often associated with lodging could not be taken as causal, but could alter the susceptibility of a crop to lodging.

Field and laboratory studies also found that stem lodging was relatively uncommon and that plants more commonly failed by root lodging (Ennos, 1991; Crook & Ennos, 1993). Working with saturated soils (i.e. weak soils), they studied the mechanics of root lodging in detail and found that anchorage of winter wheat is provided by a cone of rigid crown roots emerging from the stem base. During root lodging, this cone rotates at its windward edge below the soil surface, the soil inside the cone compressing the soil beneath. Experiments were carried out which showed that differences in anchorage strength between varieties were due mainly 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 angle of spread of crown roots as a possible indicator of lodging resistance.

Easson *et al.* (1992) observed the process of lodging in more detail than had been achieved previously 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 24 h after rainfall with wind speeds at crop height averaging > 25 km/h (6 m/s). However, lodging also occurred following rainfall when wind speeds did no exceed 16 km/h.

Baker (1995) developed a theoretical model for the windthrow of wheat plants and forest trees. Baker showed that, in the case of wheat plants, intermittent gusts of wind cause the plant to undergo damped harmonic oscillations (deflections) which impose a maximum bending moment on the stem base and roots of the plant. By calculating the resistance of the stem base and structural roots to the force imposed on them, simple failure criteria were then used to predict failure wind speeds. The main conclusion from the theoretical model work of Baker was the importance of the natural frequency of oscillation as a basic parameter in determining plant stability. Baker showed that the model explained the static instability of cereals in situations where rainfall occurred but where wind speeds were very low. For example, failure at wind speeds of 12 m/s was predicted to occur by loss of root anchorage rather than stem breakage (when using root failure moments calculated from wet soils).

From the literature reviewed above it can be seen that, at present, there is no simple cause of the lodging problem, although recent research such by Crook & Ennos (1993) has greatly improved the understanding of the root component involved in lodging. While Easson *et al.* (1992) have gone some way towards considering all the possible components involved in lodging, they were not able to successfully model lodging in a way that indicated avoidance and control strategies for growers. Despite the many attributes above which indicate the complexities which may act to cause lodging, there is still a perception amongst growers that the majority of lodging is caused by stem failure alone, as advocated by Neenan & Spencer-Smith (1975). Evidence strongly suggests that root lodging does occur and may predominate over stem lodging given the appropriate soil and crop conditions (Pinthus, 1973; Graham, 1983; Easson *et al.*, 1992; Crook & Ennos, 1993; Baker, 1995). There is a question as to whether widespread, severe lodging in the UK (such as in 1992) is caused predominately by root failure, which may have been associated with higher than average July rainfall. Stem lodging, however, may be more likely to occur on a more localised basis as a result of fertiliser overlapping, double drilling, stem base disease infection etc., or where soil conditions are particularly dry.

The aim here was to achieve a better understanding of the lodging process (including the processes involved, and the plant, soil, environmental and agronomic factors which control them) by applying the knowledge gained from independent findings of recent research (relating to wind aerodynamics, shoot structure, root structure and soil strength) and the observations from field experimentation. The major aim was to 'calibrate' the model of Baker (1995) and ultimately predict the risk of lodging occurring. This would improve both the understanding and perception of lodging risk throughout the industry.

2.2 The principles of lodging

2.2.1 *The influence of weather on the aerial canopy*

Over cereal canopies, wind structure takes on a distinct form with isolated gusts entering the canopy at intervals of several seconds causing the plants to deflect and then to oscillate at their natural frequency until the next gust arrives (Finnigan, 1979a; 1979b). Baker (1995) used a mechanical model in a time domain analysis to predict the response of a plant to a step wind input (as described above), where the maximum gust speed expected in any one hour would generate the maximum base bending moment. The moment produced at the plant base is a product of the force imposed by the wind, the force imposed by the aerial parts of the plant (such as ears and leaf canopy) and the distance from the plant ear to the plant base/roots. Structure and arrangement of tillers, leaves and ears will effect resistance of the crop canopy to air movement and thus determine the moment imposed on the plant base (Sylvester-Bradley & Scott, 1990). Pinthus (1973) states that stem length and ear shape affect the magnitude of the aerial force generated. Easson *et al.* (1992) also stated that ears interact more strongly with the wind than the rest of the plant, due to the highly ridged surface area causing high drag properties. As a result, a high proportion of the initial bending force was attributed to the ear which also acted as a weight. The weight of ears and leaves also contributes to the moment generated around the plant base, and heavy rainfall was found to increase canopy weight and increase the risk of lodging (Easson *et al.*, 1992). Neenan & Spencer-Smith (1975) found that ear weight increased by up to 30% following prolonged rainfall. Sylvester-Bradley & Scott (1990) suggest that weight distribution down the stem may be affected by wetting which would cause a greater moment on the stem base. The literature reviewed here shows that both wind and rain are important components which act upon the crop to generate forces which must be resisted by the plant base. Canopy structure is another important factor affecting these forces with large vegetative canopies and heavy, lax leaves producing a greater lodging risk (Fischer & Stapper, 1987).

2.2.2 *The mechanics of stem failure*

The first part of this section provides definitions of the important stem base properties involved in the mechanical failure of cereal stems. Codes used for the various mechanical properties can be found in the Model Engineering Codes. The descriptive terms 'stem strength' and 'stem stiffness' are commonly used by farmers, agronomists and plant breeders. It is important that these terms are accurately defined as their usage can be misleading. Strength is the load at which a structure breaks and is governed by the material properties and the geometry of the stem (Easson *et al.*, 1992). From an engineering viewpoint, the term 'stem strength' is rather inaccurate because it can easily be misinterpreted; a better term is the 'stem failure moment' or 'base bending moment at failure' which is the moment required at the stem base to cause stem failure (Baker, *pers. comm.*). If the stem is to fail at the base, the bending moment there must exceed $I\sigma/a$ (Baker, 1995). Young's modulus of elasticity (E) is the ratio of the stretching force per unit of cross-sectional area to the elongation per unit length (i.e. ratio of stress:strain). It is entirely dependent on the bonds between the molecules of which a material is composed, and is independent of the geometry of the structure (Easson *et al.*, 1992). Young's modulus is often described as 'stem stiffness', a term often used by plant breeders to describe the inherent stiffness of a particular variety. Another commonly used term is the flexural rigidity which is the tendency of a columnar structure (such as a wheat stem) to bend. Flexural rigidity (E x I) is governed by Young's modulus (E) and the second moment of area of the cross-section (I). Flexural rigidity is not stem strength but is a measure of the stem's ability to bend. It is dependent on the geometry of the stem (stem radius (a) and stem wall width (w)) but is not dependent on the material component of the stem (Easson *et al.*, 1992).

The occurrence of stem lodging depends on a combination of factors including the forces exerted on the plant by wind and rain (Pinthus, 1973), on stem bending strength and on the stem's resistance to buckling (Neenan & Spencer-Smith, 1975). In cereals, forces acting on the upper part of the plant (e.g. wind and rain) cause a turning moment which is the product of the force applied multiplied by the stem height (Jones, 1983). Stresses are induced by the aerial moment which causes deformation (stem bending). Stem bending is resisted by the stem base bending moment (the maximum of which is equivalent to 'stem strength') and by the below-ground root base bending moment (Pinthus, 1973; Grace, 1977; Jones, 1983). The elasticity of the plant causes it to return to its original position after bending but, if deformation occurs beyond the elastic limit, the plant will lean permanently i.e. become partially lodged (Jones, 1983). Stem bending is inversely proportional to the flexural rigidity (EI) for the stem material (Baker, 1995). According to Jones (1983), 'stiff' stems with large values of EI will show little deformation and will transfer the forces operating on them directly to the root system, and are therefore, more likely to promote root failure. A review by Pinthus (1973) found that stem length, which acted as the lever of the induced moment, was associated with lodging and that properties of the basal stem internodes should also affect lodging resistance. Pinthus found that varietal differences in lodging resistance were significantly associated with the diameter and wall thickness of the basal internodes, which also affected the dry weight per unit length of stem. Increased stem diameter and stem wall thickness increased stem strength. Crook, Ennos & Sellers (1994) found that stem bending strength was correlated with the amount of lignified material around the stem wall. Furthermore, Travis *et al.* (1995) found that the anatomical features of the wheat cv. Norman were consistent with stem weaknesses caused by thinner, smaller cells than the cv. Riband (rated with a higher standing power by NIAB). Travis *et al.* (1993) described a method of estimating plant cell wall thickness and cell size by image skeletonization, which may be useful for investigating variation of the above in lodging resistance studies (Dunn & Briggs, 1989).

2.2.3 *The mechanics of root failure*

It is important to have some understanding of root morphology when considering the role of roots for structural support of the plant. Klepper *et al.* (1984) found that up to three to six seminal roots develop from the base of the crown. The seminal roots are primarily for nutrient uptake and are largely unthickened (Gregory *et al.*, 1978; Klepper *et al.*, 1984; Ennos, 1991). Crown roots develop from the coleoptile and main stem nodes, and generally nodes one to six of the main stem remain below-ground to form the crown (Klepper *et al.*, 1984; Kirby, 1994). Crown root development is also associated with tiller production and, as a result, between five to 20 crown roots emerge from the crown and stem base perimeter in the mature wheat plant (Barraclough, 1984; Klepper *et al.*, 1984). Crown roots have root hairs and usually have soil attached to their basal regions. The crown roots are thicker and stiffer than seminal roots, and are lignified in the basal regions which makes them suitable for providing structural support to the plant (Dexter, 1987; Fitter & Ennos, 1989; Ennos, 1991).

The forces generated in the shoot system must be resisted by the root system. It is important to note that stems resist aerial forces on a single stem basis, whereas roots operate on a plant basis and must resist aerial forces from each shoot. The occurrence of root lodging depends on anchorage strength of the crown root system (Crook & Ennos, 1993; 1994) and soil strength/structure (D.B.Davies, *pers. comm.*). Recent research has shown that the anchorage of winter wheat is provided by a cone of rigid crown roots and, that during root lodging, this cone rotates (slips) at its windward edge below the soil surface together with the soil held within the cone (Crook & Ennos, 1993). Anchorage strength should, therefore, depend on the size of the cone and the strength of the crown roots and soil (Crook & Ennos, 1994). 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, the volume of soil occupied by the roots is low producing a small, circular root-soil plate, prone to shearing due to rotational forces. However, if crown root spread is good, a greater volume of soil is held producing a larger, more elliptical root-soil plate, more conducive to resisting rotational forces. Work by Graham (1983) also showed that root failure may occur due to stretching and/or breaking of the roots through tension, provided movement is not restricted too much by the surrounding soil, in which case the stem will have to resist the bending moment directly. Most authors are in agreement that the roots cannot be considered separately from the soil (Graham, 1983; Easson *et al.*, 1992; Crook & Ennos, 1993) and that initial failure is likely to occur in the soil particles adhering to the crown root cone.

2.2.4 *The mechanics of soil strength*

The importance of soils to the lodging phenomenon is the least researched and least understood of all areas considered here. There is little knowledge of the influences of different soil types and of the structure of soils. There are difficulties in taking appropriate measurements in the field. The available evidence suggests that the soil type and structure is a very important determinant of whether or not lodging is likely to occur (Graham, 1983; Easson *et al.*, 1992; Crook & Ennos, 1993). It is important that the effects of soil type (i.e. texture and organic matter content), soil moisture and soil compaction on the strength of surface soil are more fully understood, because these factors are the prime determinants of soil strength (D.B.Davies, *pers. comm.*).

Soil strength can be defined as the resistance of a soil to fracture by an applied shear stress or to deformation by a compressive stress (ADAS, 1982). Soil shear strength is an integral factor which affects the root lodging process during which the root cone rotates in the soil (Crook & Ennos, 1993). Soil shear strength is a function of cohesion between soil particles which is highly dependent on soil moisture content. Coherence is the primary attractive force when soil is dry but, as soil moisture increases, cohesion becomes the predominant force governing consistency (ADAS, 1982; J.R.Archer, unpublished), and is likely to be important during root lodging when the soil is moist or wet. The strength of soils is affected by many factors but the most important of these are probably clay content, soil moisture and the degree of soil compaction, which can be affected by soil management practices (Davies *et al.*, 1986). The amount of soil organic matter is also an important factor affecting soil strength (Russell, 1988), especially at sites where the % organic matter (OM) is substantially greater than the normal content for the soil type. This could occur if large quantities of organic matter had been applied to a field for a number of years.

For any mode of rupture (tension, shear or compression) and for most soils, soil strength and compaction is increased by drying (Guerif, 1994). Soil strength is also dependent on compaction, as it increases the number of particle-to-particle contacts and thus enlarges the binding forces between elementary particles (Barnes *et al.*, 1971; Guerif, 1994). Crook (1994) used three levels of soil cultivation to produce 'loose', 'normal' and 'compact' seedbed structures and showed that the anchorage strength of plants was greatest in the compact seedbed and lowest in the loose seedbed, indicating that root lodging would be less likely under compacted soils. However, Crook (1994) showed that crown root structure was unaffected by cultivation treatment (which conflicted with findings from Finney & Knight (1973)), and that anchorage strength differences appeared to depend primarily on the soil shear strength. Waldron & Dakessian (1981) used a root-soil model to predict the influence of soil shear strength on root strength for barley. A comparison of model simulations with experiments showed that the strength of the soil-root bond was the most important model parameter and that its value, rather than root strength alone, limited root lodging resistance in saturated clay loam soils.

The individual particles in soil form clods and crumbs bound together by colloidal material. The nature and size distribution of aggregates, and that of pore space, is referred to as soil structure and plays an important role in determining soil physical properties and hence soil fertility (Russell, 1988). Various factors influence the stability of soil structure such as cultivation operations (especially when the soil is wet) and environmental forces such as raindrop impact, freezing and rapid wetting of dry materials. Consequently, there is no single method for measuring stability of soil structure that is appropriate for all circumstances (Russell, 1988). The relationship between soil strength and soil structure (affected by the degree of compaction) could be assessed using the ADAS Visual Structure Score (ADAS, 1982). An 'St score' (score of soil structure) of 1 indicates a very compacted plough layer which consists entirely of dense closely fitting clods with roots only in cracks. An St score of 9 indicates a plough layer consisting mostly of porous crumbs with a few porous aggregates and very few dense aggregates (ADAS, 1982). Soil structure is undoubtedly important in terms of root lodging risk, as many clay soils weather at the surface to form a 'natural' tilth 2-3 cm deep, and work by the author showed that this phenomenon tends to reduce the strength of the surface layer as the season progresses. Conversely, weakly structured soils, such as the Bromyard silty clay loam in Herefordshire used in this work, tend to 'slump' at the surface due to rainfall producing a more compact and stronger surface layer. D.B.Davies (*pers. comm.*) suggested that cracked soil was important in terms of soil-water flow and infiltration rates in July. In a dry well cracked soil, rainfall will break up the clay into smaller aggregates, therefore decreasing the bulk density and soil strength. Wetting by heavy rain causes additional disintegration because of the impact of the faster large raindrops (Russell, 1988). Cracking may also lead to uneven wetting fronts, due to water infiltrating the cracks more readily than the uncracked soil surface (Russell, 1988).

An account of the influence of clay content, soil moisture and soil structure (compaction) on soil strength, and how this may be incorporated into the current model, is given in Chapter 7.

2.3 The importance of agronomic practices to lodging risk

In an attempt to improve predictions of crops which may acquire a high risk of lodging, it is important to consider the main agronomic practices used when growing winter wheat, and to assess the 'common perceptions' about those which most affect lodging risk.

2.3.1 *Variety*

The recommended list of cereal varieties is published annually by NIAB and provides guidance on straw length and the standing ability of varieties (NIAB, 1998). The results of a large number of ADAS experiments have shown how varieties of winter wheat with poor standing ability often justify sequential applications of chlormequat followed by a later applied ethephon-based PGR (J.H.Orson, *pers. comm.*). One of the main reasons why stem failure is perceived to be the predominant type of lodging by many growers could be due to the emphasis placed on stem strength, stiffness and shortness by varietal guidelines and PGR manufacturers. Very little consideration is given to the structural roots and anchorage of particular varieties. These facets not presently assessed and included in the UK Recommended List, such as root structure, may also be important in more fully understanding the links between variety and lodging risk.

Table 2.1 The relationship between standing power and % lodging of winter wheat varieties in contrasting seasons.

Variety	Standing power	% Lodging 1992	% Lodging 1994
Buster	9	2	1
Riband	8	16	2
Hereward	8	12	2
Brigadier	7	26	7
Hunter	7	28	3
Mercia	6	45	11
Hussar	6	46	12

Source : Fenwick (1995).

The data in Table 2.1 show that varieties rated with a high standing power by NIAB lodge less and that, although the actual levels of lodging varies between seasons, the relative differences between varieties are maintained (Fenwick, 1995). The review by Fielder (1988) provided evidence of a relationship between inherent standing power of varieties and their ability to yield well when sown early. Yields of varieties with poor standing power were reduced with early sowing (mid-September). Conversely, strong strawed varieties were amongst the most suitable varieties for early sowing, as they lodged later and less severely than most other varieties and gave relatively high yields. Resistance to lodging is an important criterion when selecting varieties for early sowing (Spink, Clare & Kirby, unpublished). In 1992, the better standing varieties Riband, Hereward and Spark (NIAB rated 8, 8 & 7 respectively) did not lodge, whereas the poor standing varieties Norman and Galahad (NIAB rated 6) both lodged severely (with up to 75% area lodged). A question arises as to the assessment of standing power which is currently determined solely from lodging score data recorded in trials (NIAB, 1993; 1998). It is likely that standing power is in fact a multi-composite character which will probably be affected by a number of plant parameters, such as plant height, canopy size, stem base structure and crown root structure.

Varieties with a high tiller production (and a high tiller survival) will initiate a greater number of crown roots than varieties with a low tiller production (Klepper *et al.*, 1984) and should therefore have better anchorage capabilities. High tillering can produce plants with wider stem bases and wider crown root spread in the soil, both of which will be beneficial to plant anchorage and support (Griffin & Berry, unpublished). For some high tillering varieties, the internodes arising directly from the crown orientate parallel to the soil surface with the stem only achieving a vertical orientation at a higher node. These stems may be better able to resist the compressive forces generated on the leeward side of the plant during bending by leaning on the soil surface (Easson *et al.*, 1992). This type of basal structure related to tillering may also be produced by rolling in the spring (Crook, 1994). Height is an important factor affecting lodging risk, with differences of up to 20 cm in height between the shortest and longest recommended wheat varieties (NIAB, 1998). There is a strong relationship between straw length and standing power for varieties (Sylvester-Bradley & Scott, 1990).

2.3.2 *Sowing date*

In the UK, wheat can be sown over a wide range of dates normally starting in early September and continuing, in some cases, to the 'latest safe date' (NIAB, 1998). Early sowing of winter wheat increases straw length, crop biomass and eyespot which markedly increase the risk of lodging (Clare, 1989).

Table 2.2 The effect of sowing date on straw height and lodging of winter wheat at Trumpington, Cambridgeshire in 1981/82 (means of 20 varieties).

Sowing date	Straw height (cm)	% crop lodged
09-Sept	93	34
30-Sept	83	15
21-Oct	76	1
02-Dec	72	0
28-Jan	76	0

Source : Clare (1989).

Table 2.2 shows how earlier sown crops usually produce taller plants. They also tend to build up a heavier canopy biomass than later sown crops and, as a result, usually represent a greater lodging risk because the crown roots have to support a taller, heavier plant (Fischer & Stapper, 1987). Vincent & Gregory (1989) reported that early-sown crops had larger root systems than late-sown crops up until early summer. It therefore seems likely that the shoot effect is partly but not completely counteracted by a root effect. Experiments done by Milford *et al.* (1993) found that early, September-sown wheat crops made better use of available soil residual nitrogen, grew and developed faster, and yielded more grain than October-sown wheat. However, Milford *et al.* also showed that in some early-sown crops, the early advantage in size and N uptake resulted in enhanced production of straw rather than grain. Both Fielder (1988) and Kirby *et al.* (1985) found that straw length in winter wheat was increased by early sowing and that lodging was frequently an important factor with the most severe and extensive lodging occurring on early sown treatments. This trend was particularly marked in 1985 when severe weather in late summer adversely affected early drillings at most sites, possibly causing the poor yields recorded nationally. From sowing date x variety experiments in 1992-93, Kirby *et al.* (1995) also reported that lodging was more severe in early sown crops (see Table 2.3) and occurred earlier in the season. Lodging was an important, perhaps dominating factor affecting grain yield. Lower harvest indices were found for the early sowing date than for the late sowing date, which appeared to be an effect of lodging rather than sowing date (Kirby *et al.*, 1995).

Table 2.3 The effect of an early and late sowing date on lodging of winter wheat at Cockle Park, Northumbria in 1993.

Variety (NIAB standing power)	Early sown (04-Sept) % area lodged	Late sown (13-Nov) % area lodged
Cadenza (6)	96	0
Avalon (6)	>85	0
Beaver (6)	>85	0
Rascal (6)	>85	0
Spark (7)	33	0
Riband (8)	43	0

Source : from Kirby *et al.* (1995).

In 1992-93, only small amounts of lodging occurred in the later sown crop and only weaker standing varieties lodged, which included Hussar, Mercia and Torfrida all with a NIAB rating of 6 (Kirby *et al.*, 1995). Stapper & Fischer (1990) found that lodging could be minimised by delaying anthesis with later sowing dates, as this reduced both crop height and dry weight at anthesis.

2.3.3 *Seed rate*

High seed rates result in a high plant population per square metre. As a result, individual wheat plants are more limited for space, nutrients etc. by competition from other plants and generally, therefore, fewer tillers are produced. This gives rise to fewer crown roots and a smaller crown root system. Observations have shown that the use of low seed rates produces lower plant densities, whereby individual plants can take advantage of this by tillering more profusely and producing a much wider and stronger plant base (Easson *et al.*, 1992). There is a strong correlation between tillering and crown root production so high tillering, encouraged by lower plant densities, will result in more structural crown roots and better plant anchorage (Klepper *et al.*, 1984). Stapper & Fischer (1990) found that low seed rates or wide row spacings decreased lodging risk, with no significant reduction in yields.

Table 2.4 The effect of seed rate on grain yield and lodging of winter wheat at Hillsborough, Northern Ireland in 1990 (means of four varieties).

Seed rate (seeds/m^2)	% lodging at harvest	Grain yield (t/ha 15% MC)
1600	100	2.79
800	100	4.19
400	90	5.63
200	39	7.81
100	10	9.65
50	6	9.51

Source : Easson *et al.*, (1993).

Easson *et al.* (1993) found that seed rate has a direct effect on the occurrence of lodging (see Table 2.4). The highest seed rate almost completely lodged (in all varieties) at the beginning of June (before anthesis) which substantially reduced grain yield. Substantial lodging occurred between mid-June and early-July at 800 seeds/m^2. Lodging at 400 and 200 seeds/m^2 then occurred progressively later in July and August. The lowest seed rates of 100 and 50 seeds/m^2 showed only very small amounts of lodging. A comparison of plants from lodged and unlodged plots indicated that, at the higher seed rates, lodged plants had basal internodes with smaller diameters and fewer support roots per stem (Easson *et al.*, 1993).

2.3.4 *Drilling depth*

Many growers suggest that altering drilling depth affects the plant's ability to resist lodging. However, the depth of drilling may not actually alter the relative depth of the crown itself, except where seed depth is less than normal crown depth due to shallow drilling or broadcasting of seed. According to Austin & Jones (1975), complex plant responses 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 only just below the soil surface. However, deeper drilled plants will often form 'double-anchorage' due to structural roots which emerge from the coleoptile node (originated from the seed) and which may improve anchorage resistance (Klepper *et al.*, 1983; Kirby, 1993). Depth of drilling may also have an influence on the angle of crown root spread which has been shown by Pinthus (1967) and Ennos (1991) to confer lodging resistance. The seed treatment 'Baytan', widely considered by growers to reduce lodging risk, was found to significantly increase crown depth and increase the number of structural coleoptile roots compared to an untreated control (Montfort *et al.*, 1996).

2.3.5 *Nitrogen*

Autumn nitrogen (N) application is not advisable because if the soil has a high N availability, or the crop is late drilled (smaller autumn N demand), or there are high N residues from the previous crop, the N recommendations are often imprecise (Sylvester-Bradley & Chambers, 1992). The amount of N required by a crop in autumn is difficult to predict but is usually sufficiently covered by natural nitrogen mineralisation, which is often under-estimated. Extra autumn N can result in excessive nitrogen supply and severe lodging (R.Sylvester-Bradley, *pers. comm.*). Early spring application of nitrogen increases tiller production and straw length which tend to make crops more prone to lodging, and so may be particularly influential if high soil N residues are present e.g. after a dry winter (less leaching of N) and if a high fertile tiller number is expected (Clare *et al.*, 1994).

Table 2.5 The effect of amount of nitrogen (N) on various lodging risk parameters.

Plant character	High N (240 kg/ha)	Low N (160 kg/ha)
Stem morphology		
Height	*taller*	*shorter*
Centre of gravity	*higher*	*lower*
Self-weight moment	*greater*	*smaller*
Stem base properties		
Bending strength	*weaker*	*stronger*
Bending rigidity (stiffness)	*NS*	*NS*
Young's modulus	*lower*	*higher*
Diameter	*NS*	*NS*
Internode dry wt cm^{-1}	*lower*	*higher*
Crown root properties		
Angle of spread	*NS*	*NS*

Crown root number	*lower*	*higher*
Root bending strength	*weaker*	*stronger*
Anchorage strength	*weaker*	*stronger*

Source: Crook (1994). *NS* = non-significant result.

Crook (1994) found that lodging occurred in plots of high N input (240 kg/ha) but not in plots of lower N input (160 kg/ha). High nitrogen increased the self-weight 'overturning' moment probably due to an increase in stem height, and also weakened both the basal strength of the stems and anchorage strength of the crown roots (Table 2.5). Easson *et al.* (1992) also found that high nitrogen decreased the stem bending strength.

2.3.6 *Plant growth regulators*

The use of PGRs on cereals is an important aspect of crop husbandry (Rademacher, 1991). PGRs are applied to cereals in an attempt to restrict stem extension and thicken or strengthen the stem, with the primary aim of preventing lodging (Woolley, 1992; Milford, 1991). Humphries (1968) reported that lodging control is also associated with accompanying increases in grain yields. However, claims made by some PGR manufacturers of yield benefits from the use of PGRs in the absence of lodging are often inconsistent (Green, 1986). The apparent inconsistency of the influence of the PGR chlormequat (chlorocholine chloride) on cereal growth has been found from experiments by Woolley *et al.* (1991) where yield benefits were obtained in the absence of lodging, which had not been the case in previous experiments performed.

Table 2.6 The main PGRs currently available for use on winter wheat.

Active ingredient	Application time	Example product
chlormequat	GS 30-31	CCC
chlormequat + 2-chloroethylphosphonic acid	GS 30-39	Upgrade
chlormequat + choline chloride	GS 30-31	New 5C Cycocel
chlormequat + choline chloride + imazaquin	GS 30-31	Meteor
2-chloroethylphosphonic acid	GS 37-45	Cerone
2-chloroethylphosphonic acid + mepiquat chloride	GS 32-49	Terpal
trinexapac-ethyl	GS 30-39	Moddus

Source: The UK Pesticide Guide, 1997 (CABI).

Traditionally, the application timings of PGRs to cereals has been between Zadoks growth stage (GS) 30-39 (Zadoks *et al.*, 1974) but, in recent years, the introduction of new products (such as ethephon-based PGRs) has enabled later applications up to GS 45 (J.H.Orson, *pers. comm.*). However, the efficacy of PGRs tends to depend on the environmental conditions and the physiological state of the plant at application and greater precision in the timing of PGRs would improve growth regulator reliability in cereals (Woolley *et al.*, 1991; Woolley, 1992).

PGRs have three basic modes of action: anti-gibberellin activity; production of ethylene compounds; and amino-acid inhibition (Hay & Walker, 1989; Anon., 1994). The active ingredients chlormequat, choline chloride and trinexapac-ethyl (see Table 2.6) are effective through reducing gibberellin activity which shortens the lower internodes (Hay & Walker, 1989). To be effective, gibberellin inhibitors need to be applied to plants in good growing conditions when the plants will be producing gibberellins to control and promote the commencing growth. Gibberellin inhibitors are therefore less effective in colder temperatures when plant growth is restricted (J.H.Orson, *pers.comm.*). Ethephon-based PGRs (e.g. 'Terpal') produce ethylene which inhibits cell elongation (Hay & Walker, 1989), and the later application timing of such products causes the middle (GS 32-33) or upper (GS 39-45) internodes to shorten (Clare, 1989). As the middle and upper internodes are naturally longer than the basal internodes and the weather during their expansion is usually ideal for the action of PGRs, the ethylene releasing products are more reliable at regulating straw length than the gibberellin inhibitors (Clare, 1989). Finally, some PGRs such as imazaquin limit the production of new cells by inhibiting amino-acid synthesis (ADAS, unpublished).

Rhone-Poulenc claim that their PGR 'Cerone' (2-chloroethylphoshonic acid) increased the straw breaking strength of cereals by 18% (Anon., 1994). However, Crook (1994) showed that chlormequat-based or ethephon-based PGRs did not increase stem strength or root strength, although they did reduce plant height so that the overturning moments generated were less (Table 2.7). Stem bending rigidity and Young's modulus of elasticity were reduced by PGRs (Crook, 1994) resulting in a reduction of stem stiffness, contrary to claims by some manufacturers.

Table 2.7 The effect of PGR application on various lodging risk parameters.

Plant character	Nil lodging control	PGR applied (5C+T)
Stem morphology		
Height	*taller*	*shorter*
Centre of gravity	*higher*	*lower*
Self-weight moment	*greater*	*smaller*
Stem base properties		
Bending strength	*NS*	*NS*
Bending rigidity (stiffness)	*higher*	*lower*
Young's Modulus	*higher*	*lower*
Diameter	*narrower*	*wider*
Internode dry wt cm^{-1}	*NS*	*NS*

Source of data: Crook (1994). *NS* = non-significant result.

Easson *et al.* (1992) also found that neither chlormequat- nor ethephon-based PGRs increased root strength or root diameter. Fischer & Stapper (1987) found that PGR applied at the recommended stages was effective in reducing plant height but did not significantly reduce lodging nor result in a positive yield response to lodging. The main benefits from chlormequat-based PGRs are in the reduction of lodging by shortening of the basal internodes (Bragg *et al.*, 1984; Green, 1986), with less consistent evidence suggesting that stem strength is significantly increased (Crook, 1994), or that, number of shoots and root growth is increased (Bragg *et al.*, 1984).

Various PGR-use schemes exist which are designed to help the grower decide on the most appropriate PGR programme that should be selected and used for a particular crop or field, such as the BASF 3-Step PGR-use Guide (BASF, 1995a). Largely based on empirical evidence, schemes such as this provide guidance for PGR-use but do not provide a quantitative risk of lodging. Currently, PGR application advice is based on factors such as sowing date, field lodging history, variety standing power, potential market, nitrogen use and yield potential (e.g. BASF, 1995a). The decision to apply lodging control should use the factors mentioned above but should also depend on an assessment of the 'state of the crop' itself, in order to predict the potential for large, rain-trapping crop canopies, weak stem bases and poor anchorage, later in the season (Clare *et al.*, 1996).

2.4 The effect of lodging on yield and grain quality

The effect of lodging on grain yield is dependent on both the severity and time of lodging as well as the weather conditions prevailing after lodging has taken place (Mulder, 1954 (cited in Pinthus, 1973)). Early lodging before anthesis, during the period of stem elongation, may hardly affect grain yield because the stems often rapidly recover to an upright position through intercalar growth of nodes, although such a crop would be more prone to lodging later in the season (Mulder, 1954). Lodging close to maturity also has no direct affect on grain yield but may cause losses due to harvesting difficulties (Pinthus, 1973). Both Mulder and Pinthus concluded that lodging at ear emergence and early grain development cause the most detrimental effects on yield. Experiments done by Mulder found that the average 1000-grain weight for upright wheat was 44.6 g compared to 32.8 g for lodged wheat, and grain yields were up to 50% greater for unlodged crops. Yield losses of this amount were ascribed to reduced carbon dioxide assimilation, resulting from leaf foliage and other photosynthesizing parts being shaded by lodged plants lying on top of them.

Shrivelled grain and reduced specific weights were commonly observed from lodged crops. Also, the moisture content of grain from lodged crops is usually greater than that from upright crops, resulting in increased drying costs (Pinthus, 1973). Fischer & Stapper (1987) studied lodging effects on high-yielding crops of irrigated semi-dwarf wheat. They found that stem lodging to an almost horizontal position caused a 7-35% reduction in grain yield, with the greatest effect when lodging occurred in the first 20 days after anthesis (i.e. late June). Grain number per ear was reduced by early lodging and grain weight was reduced by later lodging. An increase in pre-harvest grain sprouting was also found when rainy conditions occurred during ripening. Fischer & Stapper reported that lodging after anthesis reduced crop growth rate and that the adverse effect of lodging on grain yield was caused by the resulting reduction in photoassimilate supply. Crops where lodging had least effect on grain yield were characterised by a reduced degree of source limitation during grain filling. Work by Stapper & Fischer (1990) showed that lodging duration between 7 days after mid-anthesis and maturity was found to best explain early and late lodging effects on yield. Yield reductions due to lodging were up to 45%. Experiments done by Easson *et al.* (1993) showed that grain yield was correlated with the average lodging from ear emergence to harvest, with a 1 t/ha yield loss for each 10% increase in the average area lodged. The yield loss was attributed to a decrease in grain number per ear and thousand grain weight (TGW). As lodging can directly affect yield, there is a strong correlation between the amount of lodging and reduction in yield (Easson *et al.*, 1993). Thus, by reducing lodging, PGRs will prevent yield loss. ADAS trials (from 1965) with chlormequat products on winter wheat have shown a mean yield response of 0.17 t/ha; the mean was 0.06 t/ha on non-lodged sites and 0.6 t/ha on lodged sites (Woolley, 1992).

Finally, yield losses caused by lodging can also be associated with plant diseases, especially eyespot, where severe attacks greatly predispose the crop to lodging and cause high yield losses (ADAS, 1985; Jones, 1994). Severe attacks of take-all (*Gaeumannomyces graminis* var. *tritici*) also cause high yield losses and may also increase root lodging risk due to direct destruction of the structural crown root system (ADAS, 1981; Hornby & Bateman, 1991). However, severe take-all expression is also associated with light ears ('whiteheads'), which in most cases, would counteract the increased lodging risk by significantly reducing canopy weight (Yarham *et al.*, 1989; Hornby & Bateman, 1991).

From the literature reviewed here, lodging can clearly have considerable detrimental effects on both grain yield and quality (see also Chapter 1).

3. THE LODGING MODEL

3.1 The need for a wheat lodging model

The previous chapters have discussed the problems caused by lodging and the current level of understanding of the 'lodging phenomenon'. This chapter introduces the wheat lodging risk model developed by Baker (1995) which, when further developed, could act as a useful method to predict lodging risk in a crop.

It has been shown that lodging of wheat can have serious economic consequences in certain years (see Chapter 1). Despite the use of PGRs, varietal guidance and nitrogen guidelines etc., lodging is a phenomenon which is still relatively poorly understood within the cereal industry. The main problem for farmers and agronomists is therefore their inability to predict where and when lodging is likely to occur, so that expenditure on lodging control can be more accurately targeted. This is the main reason for the need to set out an analytical framework to enable the physical processes involved in lodging to be better understood. Further development of this analytical framework may then enable quantitative, if approximate, predictions of lodging risk to be made. The eventual aim is to develop the model more fully for use in the spring. It is envisaged that, in the future, the model could be adapted and used by the agronomist or farmer as a decision-making tool for lodging control. The overall scheme for reducing lodging risk would therefore be as follows :

a) early season crop assessment of various physiological parameters ;
b) from these parameters, together with a knowledge of crop growth and development, a prediction can be made of the mean crop characteristics in July when the crop is at the greatest lodging risk ;
c) this will enable a calculation to be made on the basis of these mature crop parameters to predict lodging risk at the site i.e. the probability of lodging occurring ;
d) assessment of risk to influence decision-making on lodging control measures i.e. identification of high or low risk crops, and identification at an early stage of the

principal component of the crop's structure which gives rise to that risk so that appropriate husbandry can be applied.

3.2 The model derivation

Following previous work by Roodbaraky *et al.* (1992) and Baker (1993), Baker (1995) described the development of a theoretical model for the windthrow of plants, from cereals to forest trees. The model was used to investigate the behaviour of cereal canopies under wind loading which had been shown by previous investigators to be intermittent. Wheat plants were thus assumed to be subjected to a step wind input which causes the plants to deflect and oscillate at their natural frequency until the next gust arrives. The maximum values of the base bending moment (caused by the force of the wind and the weight of the upper plant canopy) were then found, and these were used in simple stem base and root failure criteria to predict failure wind speeds.

The main assumption built into the model is that it consists of a two part system; a root and ears, connected by weightless stems. A wind gust acting on the ears will cause a restraining, rotational force from the roots, and the model predicts two natural frequencies for the system. The main model simplification was that the upper natural frequency predicted could be neglected, which resulted in a dimensionless natural frequency becoming the dominant model parameter. With the basis of the mechanical model derived, the application of wind loading was then considered. The maximum gust equation derived from the work of Greenway (1979) and Wood (1983, 1994) was used to describe the oscillation of plants subjected to wind gusts. By combining the mechanical model and the wind gust equation, a bending moment at the plant base was calculated. Finally, failure criteria were applied to the model, derived from Baker (1995) and Crook & Ennos (1993), to determine whether the total moment applied to the plant base would cause failure by either stem or root lodging respectively.

3.3 Outline of the lodging risk assessment method

The overall aim of the method is to predict the chance of lodging occurring at a particular site (or individual field) in that one year. The method predicts a risk probability for both stem and root lodging. The method depends on certain characteristics of the site, including long-term data on the wind and rain characteristics, the expected plant characteristics in the peak lodging risk period (mid-July) and the soil characteristics.

From these data, the hourly mean wind and daily rainfall probability distributions are then calculated using the site wind and rainfall characteristics. A Monte Carlo simulation technique (see Baker, 1996) is used to generate a 1000 random values for hourly mean wind speeds and daily rainfall. The shear strength and soil saturation (wetness) of the soil, along with the plant natural frequencies, are then calculated for each data set. The extreme stem base bending moment (imposed by the aerial part of the plant) that would be expected to occur in the simulated wind conditions is then calculated by using the method of Baker (1995). Simple principles of structural analysis and the root anchorage model of Crook & Ennos (1993) are then used to calculate the stem failure moment and the root failure moment respectively. By comparing the three moments (imposed moment, stem failure moment and root failure moment), the likelihood of stem and root lodging could be ascertained. The total number of occurrences of both types of lodging is then divided by 1000 to give a lodging probability. This probability is that of lodging occurring on a specific day in the lodging period. At the time of writing, an extension to this model to predict annual probabilities of lodging is under development.

3.4 The aerial component of the model

Baker (1995; 1996) assumes that the probability of the mean hourly wind speed at a particular field site exceeding a certain velocity V is given by the Weibull distribution (see equation A.1). From a knowledge of the wind speeds that are expected for 50% of the time (V_{50}) and 1% of the time (V_{99}), the Weibull parameters k_1 and k_2 can be calculated (see equations A.2 to A.5). In these equations, z_0 is the surface roughness length and h is the height above sea level. A realisation of hourly mean velocity that is consistent with the Weibull distribution can then be calculated from:

$$V = (-\ln (p_w) / k_1)^{1/k_2} \tag{3.1}$$

where p_w is a randomly generated value between 0 and 1. This velocity can then be applied to the aerial model component (Baker, 1996).

The identification of a general scheme originally used for evaluating the windthrow of trees has been suitably modified by Baker (1995) for assessing the risk of lodging in wheat. The basic model assumes that each stem of a wheat plant can be represented by an ear mass at the top, and a root mass at the bottom of a weightless but elastic stem which comes under the action of a horizontal wind force and its own mass.

This mechanical system is assumed to act as a harmonic oscillator with a natural frequency (n) and a damping ratio (c). The main output from the model is the bending moment (B) or shear force at the stem base. In particular, the maximum value of B is given for a particular hourly average wind speed. It is when this maximum value exceeds the critical value that lodging can be expected to occur. It is expected that critical values of shear force, bending moment, n and c will all be a function of crop, soil and weather conditions.

Once the values of V and n have been obtained, the value of the base bending moment for one tiller can be obtained from the method of Baker (1995). The aerial component output of the model is calculated using equation 3.2 below. This essentially relates the maximum B to the maximum gust velocity V and is given by:

$$B / (1/2\rho A C_D V_g X) = 1 + (g / (2\pi n)^2 X) (1 + e^{-2\pi c} \sin(\pi n \tau)/\pi n \tau) \tag{3.2}$$

where B is the failure base bending moment (Nm), ρ is the density of air (1.2 kg/m^3), A is the ear area (projected area of one side of the ear only) taken as 0.008 m^2, C_D is the drag coefficient, taken as 0.3 (Graham (1983)), V_g is a gust velocity (m/s), X is the centre of gravity height (m), n is the natural frequency of the stem (Hz), c is the damping ratio, taken as 0.05, τ is the loading time for a wind gust to cause failure, taken as 0.3 s and g is the acceleration due to gravity with a standard value of 9.81 m^2/s.

It is worth noting that:

a) C_D represents the dimensionless value of drag and is therefore not affected by ear size or shape for the model purposes;

b) c is estimated from published data and is included in the model as a generalised damping term, covering three effects ; internal energy dissipation in the stem and roots, aerodynamic resistance to motion and interaction with neighbouring plants;

c) τ is estimated for a cereal crop from published data on trees (Baker, 1995).

The gust velocity, Vg, is related to the mean hourly velocity by equations A.6 to A.10 (see Appendix 3). These equations involve other parameters which are: σ_v/V, the turbulence intensity, taken as 0.5 at the crop height; ${}^xL_v$, the turbulence length scale, taken as 1.25 m at crop height; and T, an observation time of one hour. Information about turbulence in a wheat crop was also considered from work by Shaw *et al.* (1977) and Baines (1982).

The natural frequency, n, is the frequency of oscillation of free vibrations of the stem (per unit time) in response to a deflection caused by a wind gust. From the analysis of Baker (1995), it is important to emphasise that the dimensionless natural frequency acts as the basic controlling parameter of the system. This single measurement encompasses both the ear's mass and length of the stem and is readily measurable within the field (see section 4.2.3). Baker (1996) has suggested that the natural frequency of the canopy/root system can be expected to be a function of whether or not the soil is saturated. The method assumes that

$$n = k_4 n_0 \qquad \text{(A.11)}$$

where n_0 is a value in dry conditions and k_4 is a constant with a value of 1.0 for dry conditions and 0.8 for saturated conditions (see section 3.6 below). Experimental findings to date have shown that saturation of the canopy due to rainfall certainly affects n, although experiments investigating differences in the levels of soil saturation on n were not conclusive as to their effects. More data are needed to estimate this model parameter. Preliminary findings by the author indicate that taller plants (with a high centre of gravity) with heavier ears predispose the plant to a low natural frequency.

3.5 The stem base component of the model

The stem base failure moment B_S (used as a failure exceedance moment) is calculated in the current model version of Baker (1995) from the formula

$$\sigma = B_S\, a/I \qquad (3.4)$$

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

$$B_S = \sigma\pi a^3 / 4\ (1-(a-w / a)^4) \qquad (3.5)$$

Values of a, σ and w need to be specified in the model programme. It should be noted that σ represents the failure stress (stem buckling) due to tension. This is unlike the approach adopted by Graham (1983) and Easson *et al.* (1992) who assumed that failure occurred due to stem buckling by compression. This different approach by Baker (1996) was a result of comparing the same stem strength values for stem failure in both tension and compression. As the stem bends, material on the outer edge is subjected to tensile forces pulling apart along the stem whilst material on the inner edge is compressed together. The model assumes that the outer edge of the stem fails in tension by flattening and 'yielding', which is probably very closely followed by the characteristic buckling of the stem on the inner, compression side, as seen in the field. In all cases, values for tensile stem failure were substantially lower than values for compressive stem failure indicating that failure in tension is the primary failure mechanism of the stem.

3.6 The root component of the model

In order to fully integrate the influence of the below ground part of the plant with the aerial model, the degree of complexity and variability of the root component needs to be developed and built into the model. The model currently describes the restoring moment at the root as a simple failure moment which is governed by certain soil conditions. Experimental work to date has suggested that the lodging moment will be a function of parameters such as soil strength, soil moisture, soil type, crown root number, crown root cone diameter etc.

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

$$B_R = k_6 s d^3 \qquad (3.6)$$

where d is the crown root cone diameter, s is the shear strength of the soil and k_6 is a constant. The constant k_6, which needs further investigation, will be a function of various parameters such as soil type, soil saturation and crown root structure. Crook & Ennos give a dimensionless value of 3.53 for this parameter which is currently used to give values for the root failure moments in the model.

The conviction by many researchers that root failure is predominant (Pinthus, 1973; Graham, 1983; Easson *et al.*, 1992; Crook, 1994) necessitates a more detailed review of root lodging and an assessment of the importance of crown root structure in supporting the plant.

The below ground root component will produce a lodging moment, B_R, i.e. a critical force required to cause soil/root resistance to fail. The smaller value of B_R or B_S for the root or stems respectively will determine whether failure occurs by root lodging or stem lodging, providing the value of B (aerial force) exceeds B_S or B_R. The value of B will vary depending on the number of stems per plant, i.e. will increase with more stems per plant.

3.7 The soil component of the model

The root anchorage model used of Crook & Ennos (1993) already incorporates a relatively simple soil component where soil shear strength is required as a determinant of the root failure moment.

It is likely that the soil moisture-soil strength relationship (for a particular soil type) will be an essential component of the below-ground root model. To date, very little work has been done in this area, although work done by Mielke *et al.* (1994) evaluated soil strength as a possible indicator of soil water content in a field situation. Extensive soil wetting tests in the field or the laboratory are needed to determine this relationship and indicate the water holding capacity of the surface layer of soil, of relevance to the lodging problem. However, Vaidyanathan (*pers. comm.*) suggested that the soil moisture-soil strength relationship may involve too many unknown variables for the limited amount of testing which could be done within the course of this investigation.

Although still relatively crude, the model has been developed by Baker (1996) to incorporate a more complex soil component than soil shear strength alone. The model currently considers two different conditions of soil moisture; when the soil is 'wet' (fully saturated to field capacity) and when the soil is 'dry' (minimum field moisture content). This step type assumption is considered necessary to simplify the complex soil moisture behaviour over the top few centimetres of soil which represents the important depth where structural crown root anchorage occurs. It can also be expected that at depths of soil of relevance to the lodging process (the top 2 to 5 cm, or more if drilled deep), soil will saturate rapidly during heavy rainfall. This will result in a rapid increase in soil moisture and a substantial decrease in the shear strength of the soil. It is also assumed that the soil will dry rapidly to this depth during the warm, bright and dry spells of weather that predominate in July.

Rainfall is important to the lodging process. It may vary from short duration high intensity rainfall to prolonged wetting from continual rain. This may to some extent determine the type of lodging likely to occur. The model currently uses daily rainfall as its basis for determination of soil saturation (wetness).

The model uses findings by Shaw *et al.* (1983) who showed that the probability of the average daily rainfall exceeding a value I is given by an exponential relationship (see equations A.11 and A.12). The exponential distribution parameter k_3 can be calculated from the daily rainfall exceeded 50% of the time (I_{50}), and a realisation of I can then be obtained from

$$I = -\ln (p_R)/k_3 \tag{3.7}$$

where p_R is a random number between 0 and 1. Once the model has calculated a value of I, the soil is taken to be saturated if :

$$I > ml \tag{3.8}$$

where m is the soil porosity, which is the volume of the soil mass occupied by pores and pore space (Fitzpatrick, 1983), and l is the crop rooting depth. Both these parameters need to be specified.

In summary, if the average daily rainfall is greater than the soil porosity multiplied by the effective rooting depth (equivalent to the crown depth or just below), then the model assumes that the soil is saturated. As with the natural frequency, the soil shear strength (s) is also expected to be some function of whether or not the soil is saturated. The current method assumes that for saturated conditions

$$s = k_5\, s_0 \tag{3.9}$$

where s_0 is a value in dry conditions and k_5 is a simple constant, given as 0.2 in the model.

3.8 The calculation of lodging probabilities

The method of Baker (1996) shows that for each pair of values of Vg and I_{50}, stem lodging will occur if

$$NB_S < B_R \qquad \text{and} \qquad B > B_S \qquad (3.10)$$

Root lodging will occur if

$$B_R < NB_S \qquad \text{and} \qquad NB > B_R \qquad (3.11)$$

where N is the number of shoots per plant, B_S is the stem base bending moment and B_R is the root base bending moment. When both stem and root lodging occur together, root lodging is assumed to occur. Therefore, by summing the number of lodging incidents predicted and dividing by 1000, the overall lodging probabilities can be found.

*What exactly does the **lodging probability** output of the model mean ?*

The predicted probability or 'lodging risk' is a certain chance of lodging occurring on a '*per day basis*' in July, at a particular site. For example, if a 50% probability is given it means that for a given day in July there is a 50% chance of getting the weather conditions to cause lodging. The predicted probabilities relate to hourly wind speeds in July in the following way: the hourly mean wind speed exceeded 50% of the time V_{50} and 1% of the time V_{99} are corrected for July, at 1 m above the crop and the site altitude (a number of constants and relationships are used for this). The corrected values are then transformed to the maximum hourly wind speed that can occur in one day. The values of V_{50} and V_{99} are then used to generate the probability distribution for the daily maximum hourly wind speeds. From this distribution, maximum hourly wind speeds are randomly selected in the Monte Carlo procedure (as well as daily rainfalls), to generate the probability of lodging occurring in one July day. The lodging probabilities are based on average plant values in the crop, so a proportion of other plants will be either more or less likely to lodge. Finally, it is worth noting that the model used here only deals with weather uncertainty, *not* knowledge or measurement uncertainty as defined in section 1.2 of Chapter 1.

3.9 Discussion of the model

Stem failure parameters (primarily a function of plant geometry) will stay relatively steady with time during the high risk July period. However, root lodging risk is likely to vary much more, depending on rainfall affecting soil moisture content and soil shear strength. Consequently, under very wet soil conditions, roots may have a lower lodging moment than stems, reinforcing the observations of Pinthus (1967) and Graham (1983) that root lodging is more common than stem lodging. However, in dry soil conditions, often with very high soil shear strengths, the force needed to overcome the soil-root resistance increases greatly making stem buckling more likely.

The probability of lodging could be determined for different parts of a field, such as the headland which is often the most lodging prone area and is not spatially uniform due to overlapping of sprays and fertilisers. A prediction of risk could also be calculated for the middle of the field where uniformity is achieved to a greater extent. Although the model would use the same deterministic approach for each area, the crop assessment would identify different parameter values likely to occur in the centre part of the field or in the headland. This approach could also be applied to the field tramlines where plants often remain upright whilst other areas are lodged.

The major model assumptions are firstly that various important crop characteristics such as crop height, ear/stem/root mass and stem and ground stiffness are all combined into a single parameter which is the basic controlling parameter of the system - the natural frequency. Baker (1995) reported a parametric investigation which showed that a 50% decrease in natural frequency caused a greater decrease in the maximum wind velocity required to cause plant failure. This was also consistent with field trial observations which showed the tendency for plants with low natural frequencies to lodge. The other advantages of using natural frequency are that it is easily measurable in the field and has a wide range of values because it is dependent on many rather variable characteristics of the plant.

The main limitations of the model at present preclude the analysis of leaning plants and fatigue-type failure. Leaning plants can be defined as plants which have partially lodged (i.e. failed to resume an upright stature). Heavy and/or prolonged rainfall may increase the weight of the canopy sufficiently enough to cause plants to lean, or the 'domino effect' of other lodged plants nearby, may cause other plants to lean. Fatigue type failure occurs through successive wind gusts progressively weakening the stem or roots. Both of these forms of failure would require a much more complex model design. At present, the model is restricted to representing the critical force required for a single wind gust to lodge the plant.

Baker (1996) reports that initial calculations of failure base bending (lodging) moments and wind speeds seem to have produced reasonable values of between 0.10-1.85 Nm and 8.6-15.0 m/s respectively. It should be noted that the failure wind speeds are for maximum gust velocities and so mean failure velocities will be about a factor of two less, resulting in predicted failure wind speeds down to about 6 m/s.

A model sensitivity analysis by Baker (1996) has identified the important model parameters which affect lodging risk which are fully tested in Chapter 6. These calculations have shown the relative sensitivity of lodging risk to various meteorological, canopy, stem base, root and soil characters. These characters are detailed in Chapter 4.2.

The main use of the model will be to enable the effects of different agronomic treatments to be compared, relative to lodging risk. The model assesses lodging risk with a quantitative approach which has not been achieved previously. However, there are many assumptions inherent in the model and a number of poorly specified parameters; it should be recognised that the model is under continual development. The predicted lodging probabilities should thus not be relied upon in an absolute sense, but rather used in a relative sense to assess the effect of changes in agronomic practices.

4.1. MATERIALS AND METHODS

4.1.1 Experimental site

The experimental work was conducted from ADAS Rosemaund Research Centre, Preston Wynne, Hereford. The experiments were carried out over three years ; the 1993-94, 1994-95 and 1995-96 seasons. The 1993-94 main experiment (MT94) was located off-site at Dormington about 10 miles from ADAS Rosemaund and a supplementary experiment (ST94) was located on-site (see section 5.1.2). In 1994-95, the main experiment (MT95) and the variety typing trial (VT95) were both located on-site, as was the main experiment (MT96) in the 1995-96 season. For experimental site details, see sections 4.1.5 to 4.1.8.

ADAS Rosemaund was chosen to conduct the experiment for specific reasons. Firstly, Rosemaund has silty clay loam soils with high organic matter content, 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 of these factors are likely to increase the chances of lodging occurring during the experimental programme.

4.1.2 Variety

The variety used in all three main experiments was Mercia. It is a non semi-dwarf variety, has a good combination of yield and bread-making quality and is fully recommended by NIAB (1995). The variety possesses moderate straw strength (NIAB standing power rating = 6) and responds well to plant growth regulator treatment (NIAB, 1995). Mercia is also being used as a standard in other HGCA-funded physiology research projects (HGCA, 1998). The ST94 trial used the variety Riband which is stiffer strawed than Mercia, with a NIAB standing power rating of 8.

The VT95 experiment, designed to provide a wide range of physiological traits (Scott *et al.*, 1994), tested both modern and older varieties:

Ami	Brigadier	Holdfast	Mercia	Scipion
Apollo	Cadenza	Hunter	Norman	Soissons
Avalon	Florin	Little Joss	Piko	Spark
Avital	Haven	Longbow	Rialto	Zentos
Beaver	Hereward	Lynx	Riband	
Maris Huntsman		Squareheads Master		

More detailed model specific measurements were taken on a subset of varieties chosen to provide a large range of lodging risk. These included Little Joss (an old, tall, high lodging risk variety), Beaver (a modern, poor standing power variety), Cadenza (a modern solid-stemmed, moderate standing power variety), Riband and Hereward (widely grown varieties with good standing powers) and finally Mercia (used as the control variety, as examined in the main experiments).

4.1.3 Experimental design

The MT94 experiment used a fully randomised split plot design with sowing date and seed rate randomised on main plots and residual nitrogen and lodging control randomised on sub-plots. Both the MT95 and MT96 experiments also used a fully randomised split plot design, but with sowing date on main plots, seed rate on sub-plots, and residual nitrogen and lodging control on sub sub-plots. Individual plot sizes were 4 m x 18 m for MT94 and MT95, and 4 m x 24 m for MT96, with three replications of each treatment combination giving 96 plots. The ST94 experiment was based on a fully randomised split plot design with sowing date randomised on main plots and lodging control randomised on sub-plots, and plot sizes were 2 m x 12 m with three replications. The VT95 trial was based on a randomised block with four replications and plot sizes were 1.8 m x 21.0 m. For trial plans see Appendix 2.

4.1.4 Experimental treatments

The rationale behind choosing the treatments described below was to set up an experiment that established an array of treatments that encompassed elements of crop husbandry that were known to be critical in determining lodging risk. Thus, testing sowing date, seed rate and nitrogen residues (two levels of each) gave a wide range of factorially combined factors to provide the extreme combinations of high and low lodging risk and numerous degrees between. Within each treatment are four sub-plots on which to compare, against a control, the three measures thought most likely to reduce lodging.

Two sowing dates were used in the main experiments. An early sowing date, TOS 1 (aimed for mid-end September) and a later sowing date, TOS 2 (aimed for mid-late October). The early sowing date was devised to produce a taller, more forward crop, with a larger canopy which should provide a higher lodging risk than the later sown crop. For the actual sowing dates for each experiment, see Site Records 4.1.5, 4.1.6 and 4.1.8. In the VT95 trial, all varieties were sown on the same date in mid-October. The abbreviation TOS is used for time of sowing.

Two seed rates were used in the main experiments; 500 seeds/m^2 and 250 seeds/m^2. The high seed rate (HSR) was devised to produce a high plant density crop with tall, weak stems and few roots per plant, which should provide a higher lodging risk than the low seed rate (LSR) crop. The ST94 experiment and the VT95 trial were both sown at 350 seeds/m^2.

Two levels of residual nitrogen were created in the main experiments to produce contrasting high and low levels of soil residual nitrogen. In MT94, this was achieved by applying 80 kg N/ha in the autumn (post-emergence on the 23-Nov-93) to the high level and none to the low level. In MT95, 330 kg N/ha and 30 kg N/ha were applied to the previous crop (spring oilseed rape) before harvest to create the high (330-ResN) and low (30-ResN) residual levels respectively. In MT96, 350 kg N/ha was applied for the high level with nil applied for the low level. The high level of residual nitrogen was devised to emulate either high residues left from the previous break crop or the practice of applying organic manure/slurries before sowing, both of which are thought to increase lodging risk.

In the MT94 experiment, soil samples were analysed (and averaged across all other treatments) and soil mineral nitrogen (SMN) was found to average 101 kg N/ha on the high residual N plots and 72 kg N/ha on the low residual N plots, a difference of approximately 30 kg N/ha. This difference in SMN between the two treatments was further increased in MT95 (40 kg N/ha) and in MT96 (45 kg N/ha), see Tables 4.1 and 4.2 below.

Table 4.1 Spring soil mineral nitrogen (kg N/ha) for the MT95 experiment.

Treatment	TOS 1 (23-Sept)		TOS 2 (19-Oct)		
	HSR	LSR	HSR	LSR	Average
High residual nitrogen	78	79	87	96	85
Low residual nitrogen	41	38	47	59	46

SED = 16.1 (23 df).

Table 4.2 Spring soil mineral nitrogen (kg N/ha) for the MT96 experiment.

Treatment	TOS 1 (20-Sept)		TOS 2 (1-Nov)		
	HSR	LSR	HSR	LSR	Average
High residual nitrogen	94	111	130	132	116
Low residual nitrogen	65	65	77	77	71

SED = 22.0 (23 df).

Four different lodging control methods were used in all the main experiments and the ST94 experiment. The first was a 'nil control' treatment (NIL), imposed to provide a high lodging risk, against which lodging control treatments could be compared. The second treatment (5C) was an application of 2.5 l/ha of new '5C Cycocel' (chlormequat + choline chloride) at GS 31. This treatment was devised to promote a 'better' stem and anchorage base in crops where long and weak stems are expected during early stem extension. The third treatment (5C+T) was as the second above, plus an application of 1.5 l/ha of 'Terpal' (2-chloroethylphosponic acid + mepiquat chloride) at GS 45. The addition of Terpal (a later applied ethephon-based growth regulator) was a treatment devised to curtail later extension of the upper stem internodes, expected to be too lush for the support generated earlier by 5C chlormequat alone. The fourth treatment, G5 (also devised to curtail later growth and reduce canopy size) was a reduced application of nitrogen at both the early dressing and the main dressing. This was followed by an additional, late application of 60 kg N/ha at anthesis. This treatment was adjusted to supplement soil nitrogen and designed to produce a canopy of green area index 5 by the end of May (ear emergence when soluble stem carbohydrates are deposited) and then to maintain the canopy for as long as possible through grain filling (Sylvester-Bradley, 1993; Anon., 1995; HGCA, 1998). See sections 4.1.5.1, 4.1.6.1 and 4.1.8.1 for treatment details.

The background behind the G5 treatment was that the main effect of nitrogen applied to wheat crops is to enlarge their leaf canopies, thereby increasing lodging risk, yet canopies enlarged beyond G5 capture little extra light. This is based on data (Anon., 1995; HGCA, 1997b, 1998) which showed that a canopy of G5 intercepts 95% of incident radiation, and for every unit of green area (i.e. ha green canopy area per ha ground area) the crop requires 30 kg N/ha. To achieve this, 150 kg N needs to be in the crop by ear emergence and then at anthesis, a 'top-up' of extra nitrogen can be supplied. The late nitrogen will not promote canopy expansion but is designed to replace nitrogen stripped from the canopy by the developing grain, and therefore prevent premature canopy death. To get 150 kg N into the crop by ear emergence, the amount of plant and soil N must assessed and the difference made up with inorganic fertiliser. To do this, the crop N content and soil mineral nitrogen (SMN) content are measured in February. A canopy of G2 is required by GS 30, so if crop N + SMN (assumed to be used with 100% efficiency) is less than 60 kgN/ha, inorganic nitrogen is applied to make up the difference (assuming an efficiency of 60%). After GS 30, further N is supplied (if needed) to attain G5, with 60 kg N/ha applied at anthesis either as solid nitrogen or foliar urea.

NB: For each experimental year, the whole site was ploughed prior to the first time of sowing. The area for each time of sowing received secondary cultivation just before drilling to produce a fine tilth. The drill was calibrated for high and low seed rates before drilling, with discards drilled at the low seed rate.

The programme of disease control for all the main experiments was aimed to keep the crop disease-free using the following prophylactic fungicide programme in each season: a) fenpropimorph or fenpropidin + prochloraz at GS 31; b) tebuconazole at flag leaf (GS 39) c) mancozeb at ear emergence (GS 59).

Weed control and pest control aimed to keep the crop free of weed competition and unaffected by pest damage respectively. Treatments were therefore dependent upon the weeds present or pests encountered locally in each trial as set out by the 1994 HGCA 'Development Project' protocol.

4.1.5 MT94 and ST94 experiments : site records

Record	**MT94**	**ST94**
Field name	Dormington	Slade Hopyard
Field altitude (m)	-	84
Soil texture & series	Bromyard - stoneless silty clay loam	Bromyard - stoneless silty clay loam
Drainage	Well drained	Well drained
Soil analysis pH	6.9	6.9
P, K, Mg : mg/l (Index)	42 (3), 176 (2), 73 (2)	85 (5), 573 (4), 108 (3)
Organic matter (%)	4.2	3.4
Previous cropping	Winter oats	Winter oilseed rape
Residual nitrogen (kg N/ha)	0 or 80	0
Cultivations Time of sowing 1 & 2	Ploughed 14-Oct SKH crumbler x2 power harrow x1	Ploughed 26-Sept SKH crumbler x1 rotavator x1
Drilling date	TOS 1 16-Oct TOS 2 8-Nov	TOS 1 24-Sept TOS 2 17-Oct
Drill type & width	Accord drill 4.24 m width	
Seed rate	250 500 (seeds/m^2)	350 (seeds/m^2)
Row width	12 cm	12 cm
50% emergence date	TOS 1 18-Nov TOS 2 14-Dec	- -
Molluscicides	Draza 5.5 kg/ha 18-Nov	
Herbicides	Glyphogan 3.0 l/ha 01-Oct Panther 2.0 l/ha 31-Jan	Panther 2.0 l/ha 02-Feb Starane 1.0 l/ha 25-May
Fungicides	Tern + Sportak 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)	Tern + Sportak 28-Apr (0.75 l/ha + 0.9 l/ha) Impact Excel 24-May (2.0 l/ha) Tilt + Benlate 16-Jun (0.3 l/ha + 0.3 kg/ha)
Insecticides	Aphox 280 g/ha 30-Jun	-
Harvest date	17-Aug-94	9-Aug-94

4.1.5.1 *Nitrogen fertiliser applications*

For the residual nitrogen applications, see section 4.1.4. For the MT94 experiment all the TOS 1 plots had 80 kg N/ha applied on the 21-Mar-94 and 120 kg N/ha applied on the 25-Apr-94. The TOS 2 plots were as above except that the 80 kg N/ha was applied on the 06-Apr-94. The ST94 TOS 1 and TOS 2 treatments had 80 kg N/ha applied on the 21-Mar-94 and 120 kg N/ha applied on the 19-Apr-94. The nitrogen applied for the G5 treatments for MT94 and ST94 is shown in Table 4.3.

Table 4.3 Nitrogen fertiliser applications (kg/ha) for the G5 lodging control treatment in the MT94 and ST94 experiments.

Application date	MT94 TOS 1	TOS 2	ST94 TOS 1	TOS 2
21-Mar-94	30	-	30	30
06-Apr-94	-	30	-	-
26-Apr-94	-	-	40	40
20-Jun-94	60	60	60	60

NB: both high and low residual nitrogen levels were treated the same.

4.1.5.2 *Plant growth regulator applications*

Both MT94 sowing date treatments had 5C Cycocel applied on the 03-May-94 at a rate of 2.5 l/ha and Terpal applied on the 19-May-94 at a rate of 1.5 l/ha. ST94 had 5C Cycocel applied (rate as above) on the 26-Apr-94 (for TOS 1) and 03-May-94 (for TOS 2) and Terpal applied (rate as above) on the 22-May-94 for both sowing dates.

4.1.6 MT95 experiment : site records

Record	MT95
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
Residual nitrogen	Low =30 kg N/ha High =330 kg N/ha
Cultivations Time of sowing 1 Time of sowing 2	Ploughed 12-Sept Power harrow x1 23-Sept SKH crumbler x2, power harrow x1 17-Oct
Drilling date	TOS 1 23-Sept TOS 2 17-Oct
Drill type & width	Accord drill, 4.24 m width
Seed rate	500 seeds/m^2 = 201.12 kg/ha 250 seeds/m^2 = 100.56 kg/ha
TGW of seed (g)	39.98
Row width	12 cm
50% Emergence date	(TOS 1) 1/6-Oct (TOS 2) 2/4-Nov
Herbicides	Javelin Gold 5.0 l/ha 16-Nov
Fungicides	Tern + Sportak 45 0.75 l/ha + 0.9 l/ha 13-Apr Corbel CL 2.5 l/ha 18-May Legend + DerosalWDG 0.7 l/ha + 0.2kg/ha 9-Jun
Insecticides	Decis 200 ml/ha 16-Nov Phantom 100 g/ha 28-Jun
Harvest date	11-Aug-95

4.1.6.1 *Nitrogen fertiliser applications*

For the residual nitrogen applications, see section 4.1.4. In MT95, all TOS 1 plots had 30 kg N/ha applied on the 08-Mar-95. A further 120 kg N/ha and 170 kg N/ha were applied to the high and low residual nitrogen plots respectively, on the 04-Apr-95. The TOS 2 plots had 80 kg N/ha applied on the 08-Mar-95, with a further 160 kg N/ha (high residual N plots) and 110 kg N/ha (low residual N plots) applied on the 13-Apr-95. The nitrogen applied for the G5 treatments in MT95 is shown in Table 4.4.

95. The TOS 2 plots had 80 kg N/ha applied on the 08-Mar-95, with a further 160 kg N/ha (high residual N plots) and 110 kg N/ha (low residual N plots) applied on the 13-Apr-95. The nitrogen applied for the G5 treatments in MT95 is shown in Table 4.4.

Table 4.4 Nitrogen fertiliser applications (kg/ha) for the G5 lodging control treatment in the MT95 experiment.

Application date	TOS 1, high residual N	TOS 1, low residual N	TOS 2, high residual N	TOS 2, low residual N
04-Apr-95	-	80	-	-
13-Apr-95	-	-	30	30
26-Apr-95	-	-	-	50
05-May-95	50	-	20	-
12-Jun-95	60	60	60	60

Nitrogen was spread on the trials either by hand, plot applicator or farm spreader. Nitrogen was applied as Nitram 34.5% N and nitrogen rates were based on ADAS recommendations for the soil type and N index.

4.1.6.2 *Plant growth regulator applications*

MT95 had 5C Cycocel applied on the 24-Mar-95 (for TOS 1) and on the 10-Apr-95 (for TOS 2) at a rate of 2.5 l/ha. Terpal was applied on the 20-May-95 for both sowing dates at a rate of 1.5 l/ha.

4.1.7 VT95 experiment : site records

Record	**VT95**
Field name/altitude	Drive Meadow / 84 m
Soil series/type/drainage	Bromyard - stoneless silty clay loam, well drained
Previous cropping	Linseed 94', Winter wheat 93', Winter oilseed rape 92'
Cultivations	Ploughed 11-Oct-94, power harrow 12-Oct-94
Drilling date	12-Oct-94
Drill type & width	Accord drill, 4.24 m width
Seed rate	350 seeds/m^2
Fertiliser	63 kg N/ha 22-Mar-95, 147 kg N/ha 28-Mar-95 40 kg N/ha (foliar urea) 06-Jul-95
Herbicides	Panther 2.0 l/ha 17-Nov-94 Starane 0.75 l/ha 15-May-95
Fungicides	Sportak 45 0.9 l/ha 08-Apr-95 Tern 750 EC 0.75 l/ha 08-Apr-95 Folicur 1.0 l/ha 18-May-95

	Silvacur	1.0 l/ha	16-Jun-95
Insecticides	Cyperkill Phantom	0.2 l/ha 100 g/ha	17-Oct-94 26-Jun-95
Molluscicides	Draza	5.5 kg/ha	28-Oct-94
Plant growth regulators	5C Cycocel	2.5 l/ha	08-Apr-95
Harvest date	08-Aug-95		

4.1.8 MT96 experiment : site records

Record	MT96
Field name	Jubilee
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	7.1
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
Residual nitrogen	low =30 kg N/ha high =330 kg N/ha
Cultivations Time of sowing 1 Time of sowing 2	Ploughed 18-Sept Power harrow x1 20-Sept Power harrow x1 01-Nov
Drilling date	TOS 1 20-Sept TOS 2 01-Nov
Drill type & width	Accord drill, 4.24 m width
Seed rate	500 seeds/m^2 = 233.0 kg/ha 250 seeds/m^2 = 116.5 kg/ha
TGW of seed (g)	46.60
Row width	12 cm
50% Emergence date	(TOS 1) 01-Oct (TOS 2) 22-Nov
Crop protection Herbicides	 01-Mar : Javelin Gold (2.0 l/ha) Isoproturon (1.0 l/ha) Cypermthrin (0.25 l/ha) 01-May : Ally (30 g/ha) 09-May : Cheetah (2.5 l/ha) Starane (0.5 l/ha)
Fungicides	01-May : Sportak 45 (0.9 l/ha) Tern/Patrol (0.75 l/ha) 30-May : Folicur (1.0 l/ha) 22-Jun : Silvacur (1.0 l/ha) Patrol (0.5 l/ha)
Insecticides	03-Nov : Metarex (7.7 kg/ha)
Harvest date	19-Aug-96

4.1.8.1 *Nitrogen fertiliser applications*

For the residual nitrogen applications, see section 4.1.4. Both the MT96 TOS 1 high and low residual nitrogen treatments had 40 kg N/ha applied on the 14-Mar-96. A further 110 kg N/ha and 160 kgN/ha were applied to the high and low residual nitrogen treatments respectively, on the 04-Apr-96. The TOS 2 treatments both had 40 kg N/ha applied on the 14-Mar-96, with a further 150 kg N/ha (high residual N plots) and 100 kg N/ha (low residual N plots) applied on the 29-Apr-96. The nitrogen applied for the G5 treatments in MT96 is shown in Table 4.5.

Table 4.5 Nitrogen fertiliser applications (kg/ha) for the G5 lodging control treatment in the MT96 experiment.

Application date	TOS 1, high residual N	TOS 1, low residual N	TOS 2, high residual N	TOS 2, low residual N
11-Mar-96	-	-	-	30
02-Apr-96	-	50	-	-
17-Apr-96	-	-	-	60
08-May-96	-	-	-	40

4.1.8.2 *Plant growth regulator applications*

MT96 had 5C Cycocel applied on 03-Apr-96 (for TOS 1) and on 25-Apr-96 (for TOS 2) at a rate of 2.5 l/ha. Terpal was applied on 02-Jun-96 (for TOS 1) and on 07-Jun 96 (for TOS 2) at a rate of 1.5 l/ha.

4.1.9 Plant sampling

Two methods of plant sampling were used for all experiments; 0.72 m^2 quadrat samples (for general crop growth and development measurements) and a sample of ten plants (including roots) for more detailed model specific measurements.

4.1.9.1 *Ten plant sampling*

Ten plants were selected randomly from around the edge of the quadrat area. The plants were carefully pulled up when soil conditions were moist or wet or dug up if soil conditions were very dry (to try and ensure that the structural crown roots did not break during sampling). The plants were placed in plastic bags and stored at 4°C until analysis.

4.1.9.2 *Quadrat sampling*

To avoid local bias in selection of samples, sampling was carried out from pre-determined areas, identified using plot marker pegs. Samples were taken using 0.72 m^2 rectangular quadrats (1.2 m x 0.6 m quadrat) orientated diagonally where possible, or parallel to crop rows, in order to sample rows more representatively (Hume & Shirriff, 1995). Samples were taken at least three rows from the ends and edges of plots or tramlines. The objective was to recover as much above ground and below ground material as possible. If conditions were very wet, to avoid soil contamination between above and below ground material, samples were cut off at the soil surface using a sharp knife, and the below ground material was dug up separately. If conditions were dry, then whole plants were pulled up instead of cutting them off at the stem base. Loose soil was shaken off and the above and below ground material was placed in labelled plastic bags. The bags were sealed to prevent drying and the samples were stored in a cold room at 4^oC.

4.1.10 Plant analysis

For laboratory growth analysis, plant material was removed from the bags and, if wet, soil was washed off gently under a running tap. Paper towels were used to remove all surface water. If plants were dry, the soil was carefully shaken off (taking care not to damage the roots) and then the roots were cut off using scissors. The above-ground sample was weighed, then spread out and half was selected at random (the other half was discarded). This was spread out again and split into three piles of which one was selected. This sub-sample (SS1), approximately 15% of total sample, was kept for growth analysis. Of the remainder, a further random sub-sample (SS2) was taken (15-20% of total sample) for oven drying. Samples were dried at 80^oC for 24 h or until the samples had reached constant weight. For the early growth stages (GS 30/31), the whole above-ground sample was used for growth analysis. The SS1 sub-sample was split into three categories of shoots; fertile shoots, dying shoots (defined as when newest expanding leaf has begun to turn yellow) and dead shoots (no green material present). Shoot number was counted for each category.

For preparation of the below-ground material sample (which included crown roots, seminal roots and stem bases), see laboratory growth analysis above. The total fresh weight of the roots sampled was recorded and then a 15-20% sub-sample of roots was randomly selected. Fresh weight of the roots sub-sample was also recorded. The roots were then placed in a tray and oven dried at 80°C for 24 h and dry weight of the sub-sample was then recorded.

4.1.11 Pre-harvest analysis

Grab samples (five per plot, taken at random along the plot length and cut off at ground level) were taken in all plots just before harvest, to determine:

Dry matter harvest index (DMHI);

Thousand grain weight (TGW);

Ear and straw fresh weight.

Fresh weight of the total sample was recorded and then all ears were cut off and counted. Total straw fresh weight was recorded. Then a random 10-15% sub-sample of straw was selected and weighed, oven dried, and dry weight determined. Total ear fresh weight was recorded. All the ears were then threshed and the grain and chaff was collected. Fresh weight and dry weight of grain and chaff (20 g sub-sample) were recorded.

4.1.12 Combining of plots and harvest analysis

Plots were combined by ADAS farm staff following a standard procedure. Prior to harvesting, tramlines were cut out, so that they did not form part of the harvested area. Plot lengths were then measured. For the harvest, one combine strip was taken through the centre of the combine area of the plot (to avoid bias due to edge effects). The width of the cut plot was accurately recorded. The area taken was approximately 10 m x 2.25 m, to determine plot yield (t/ha). For each plot, a 1 kg sample of grain was taken and saved for measurements of thousand grain weight, specific weight and grain moisture content. Plot yields were expressed as t/ha at 85% dry matter.

4.2. MODEL SPECIFIC MEASUREMENTS

The measurements described below are for the MT94, ST94, MT95 and MT96 experiments, unless stated otherwise. Only certain measurements were taken on the VT95 trial (see Chapter 5.2, 5.3 & 5.4). For specific details on measurements, sampling intervals and dates, see the experiment sampling schedules 1993-94 and 1994-95 in Appendix 2. The derivation and justification of the measurements specifically related to the model are also described in the following sections.

4.2.1 Crop growth and development measurements

The measurements outlined below all used the quadrat sampling method described in section 4.1.8.2. The fresh weight and dry weight of above-ground plant material was measured at each sampling interval. For details of the preparation of plants for growth analysis, see section 4.1.9 on Plant Analysis. For each plot, the total fresh weight of above-ground material was recorded and the dry weight measured following oven drying at 80°C. Total biomass for above-ground material was then calculated.

The below-ground fresh weight and dry weight of crown roots were measured at each sampling interval. For preparation of roots for growth analysis, see section 4.1.9. For each plot, the total fresh weight of roots was recorded and the dry weight measured following oven drying at 80°C. The biomass for below-ground material was then calculated.

Shoot number was recorded for each plot sampled. In the MT94 and ST94 experiments, shoots were split into three categories; fertile shoots, dying shoots and dead shoots. For the MT95 and MT96 experiments, fertile shoot number only was counted.

The plots were observed at least every seven days. Plant developmental stage was assessed using the Zadoks growth stage (Zadoks *et al.*, 1974; Tottman & Broad, 1987) on six plants per plot.

4.2.2 Ear geometry measurements

Unless otherwise stated, the measurements described in sections 4.2.2 to 4.2.6 were all taken on ten plants per plot using the ten plant sampling technique described in section 4.1.8.1.

The main stem ears were cut at the collar from each ten plant sample and ear area (cm^2) was measured directly using a Delta-T Devices image analyser. Ear length (cm) was measured from the ear base (collar) to tip of terminal spikelet. Ear diameter (mm) was measured on both sides of the ear (as it is not circular) using digital callipers. Ears were weighed (g) using digital Mettler scales.

4.2.3 Stem and canopy measurements

For the purpose of this section, the stem and canopy consists of internodes 3, 4, 5 and 6. The length, diameter and weight of these internodes were measured as described in section 4.2.4.

Natural frequency was measured directly by plant oscillation tests in the field. Firstly, the main stem was identified and then the other shoots and any surrounding plants were held (by hand or by using a metre rule) out of the way. This was somewhat crude so, for the MT95 and MT96 experiments, a plastic cone was used and placed over the plant (narrow neck at the base). The wide end of the cone held back the surrounding plants. The main stem was then pulled back (at the ear collar) 15 mm from the vertical and released. After release, the number of 'significant' oscillations of the stem was counted and timed using a stopwatch, and natural frequency was calculated. '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, at 90° to the original direction of release) then they were not timed.

In July 1995, natural frequency tests were also conducted under different soil moisture conditions which required artificial wetting of the soil in localised areas of the plot. In each plot, eight areas were marked using 0.25 m^2 quadrats. Differential wetting treatments were then applied to these quadrat areas to simulate 0, 10, 20, 30, 40, 60 and 80 mm rainfall. Wetting treatments were applied slowly and steadily over the plants in each quadrat (not directly onto the soil), using a watering can and rose, to try and simulate rainfall as closely as possible.

Firstly, the equivalent of 20 mm rainfall over the quadrat area was applied to the 60 and 80 mm treatments. After 2 h, another 20 mm was applied to the 60 and 80 mm treatments, and to the 40 and 30 mm treatments. After another 2 h, 20 mm was applied to the 20, 40, 60 and 80 mm treatments and 10 mm to the 30 mm treatment (now completed). After a final 2 h, 20 mm was applied to the 80 mm treatment and 10 mm to the 10 mm treatment, to complete the differential wetting. The applied water was then left to soak in overnight and allow soil moisture to equilibrate. Natural frequency tests were then conducted the following morning on each wetting treatment (ten plants per treatment). Gravimetric soil moisture and soil shear strength measurements were also taken (see section 4.2.6) at the same time as frequency was measured.

To find the centre of gravity (Crook, 1994) of the shoot system of each plant, the roots were cut off and the main stem was then balanced on a ruler to find the point of balance along the stem (leaves and ear still attached). This distance from the point of balance to the stem base was then defined as the centre of gravity (cm). Centre of gravity was also measured for the whole plant for the MT95 experiment. The same method as above 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 number of internodes was counted on each stem and recorded. Crop height (m) was measured from the stem base (soil surface) to the topmost leaf ligule or base of the ear collar (when emerged) using a metre rule. Tiller number was recorded for ten plants per plot at each growth analysis to enable the number of tillers per m^2 and shoot density to be calculated. Once the flag leaves were fully emerged, a record was made of whether they were erect or lax, and if they were prominent above the ear (i.e. likely to engage the wind).

4.2.4 Stem base measurements

For the purpose of this study, the stem base consists of the basal internode, internode one and internode two only. Stem internodes were numbered according to the following methodology which remains consistent throughout the thesis; an internode which originated at or just below the ground surface and was more than 10 mm in length was numbered as internode one. 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 preceeding internode one which were 10 mm or less in length and were generally situated just below ground level.

The diameter of the plant at the stem base (i.e. taken to be the soil surface, distinguished by a darkening of the stem where soil was adhered to it) was measured in millimetres.

Main stems of each ten plant sample were identified and their leaves pulled off. Specific internodes were then individually tested for strength after measuring internode length and diameter. 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 Etalon digital callipers.

Tensile stem failure strength was measured in grams using a vice to conduct a three-point bending test (Graham, 1983; Easson *et al.*, 1992). The vice jaws could be adjusted to the exact length of each internode. The adjacent nodes of the internode were then held against the vice jaws and a pulling pressure was applied using a graduated Salter spring balance (1 kg x 10 g or 5 kg x 25 g). 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. Stem failure stress was then calculated.

Internodes were then cut at the mid-point of the nodes at both ends and weighed (g) on Mettler PM480 digital scales. Finally, internodes were cut in half in the middle and digital callipers were used to measure the stem wall width (mm). Using the above measurements of stem failure stress (or material strength of the stem), external stem diameter (to enable stem radius to be calculated), internal stem wall width (thickness) and the stem base failure moment (equivalent to maximum strength) can be calculated from basic structural theory (Baker, 1995).

4.2.5 Root measurements

At GS 30, seed depth (mm) was measured from the soil surface (distinguishable by a junction between white and green tissue) to the seed case. The presence or absence of a sub-crown internode (which grew from the seed to the crown) was also recorded.

The number of crown roots (structural adventitious 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, see Plate 4.2.1 (Appendix 1). This distinguished them from seminal roots which were much thinner, less rigid and usually had no soil adhered to them (Ennos, 1991).

The rigid crown root length is defined as a section of root which shows high rigidity and has a similar diameter along its length, forming the basal regions of crown roots. At the end of this section, the distal regions of crown roots become considerably thinner and lose rigidity and hence are no longer useful for structural anchorage purposes (Ennos, 1991). The rigid lengths of each root per plant were measured in mm, using a ruler, to calculate the total rigid length per plant. It is worth noting that the ease at which rigid root length could be measured depended to an extent on soil conditions at the time of sampling. Under very dry, hard soil conditions, crown roots were easily broken off when being dug up in the field. Consideration should be taken for the possibility of a degree of subjectiveness due to the nature of the method. For the reasons outlined above, a more practical and less subjective method for measuring root rigidity was defined for use in the MT96 experiment. The new measurement of structural rooting depth was the length from the crown to the end of the rigid sections of the crown roots, and is measured simultaneously to the root cone

diameter. The main justification for this measurement is because it is used in the determination of the soil strength/moisture status in the below-ground model.
The angle of crown root spread (Pinthus, 1967) was measured in degrees in two planes ; plane one where the two widest or outermost roots were measured from the crown, which gave the maximum angle of root spread, and plane two where the two narrowest or innermost roots were measured from the crown, at 90° from plane one. This gave the minimum angle of root spread. The average of these two measurements was then calculated.

The diameter of the crown root cone (i.e. the structure formed by the crown roots, rigid enough to hold soil within the cone, Plate 4.2.1) was measured in mm along two planes. The maximum root cone diameter was defined as the largest diameter formed by the rigid sections (see above) of two crown roots, measured parallel to the soil surface. The minimum root cone diameter was defined as the diameter of two crown roots which is formed at 90° to the maximum root cone diameter.

The root crown is defined as the origin of all the adventitious roots, and the width of this crown was measured in mm. Measurement of crown width differed from the stem base diameter of the plant by the distance between the soil surface and the root crown.

Root resistance was measured by plant displacement tests, using an overturning 'lodging device' (referred to from here on as a 'torquemeter') designed by Ennos & Crook in 1994 (University of Manchester), see Plate 4.2.2 (Appendix 1). The hand-held 'torquemeter' 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 are 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). This type of measurement could previously only be performed in the laboratory, using an Instron materials testing rig to study the tensile force required to pull wheat roots from soil cores (Crook & Ennos, 1993; Easson *et al.*, 1995).

Areas to be tested were marked with 0.25 m^2 quadrats. In each quadrat, ten plants were tested. Root resistance was then measured using one of two methods :

Method 1, as used by Crook & Ennos (1994).

1. Select one plant and cut off the shoots at a height of 20 cm from the ground.
2. Position the torquemeter so the rotation arm rests against the cut stems.
3. Rotate the arm steadily using the rotation lever to 45°, and measure the final resting force (Nm) at 45°.
4. Release the plant and zero the rotation arm at 45°.
5. Insert the tops of the cut shoots into the hollow tube on the top of the rotation arm and measure the force (Nm).

Method 2, as used by Griffin & Berry (unpublished).

1. Select one plant and cut off the shoots at a height of 5 cm from the ground.
2. Position the torquemeter so the rotation arm (a shorter version) rests against the cut stems.
3. Rotate the arm steadily to 45° and measure the maximum force (Nm) during the rotation (using the maximum setting on the torquemeter).

Method 1 was the method used by Crook & Ennos (1994) to artificially lodge plants in the laboratory using an Instron loading machine. This same method could be used for the field based torquemeter. However, after initial testing in the field, a number of modifications to this technique were made for practical reasons. Firstly, root resistance tests were performed under highly saturated soil conditions by Crook & Ennos (see Ennos, 1991). However, under field conditions, soil was much less saturated which made root resistance more difficult to measure due to the influence of the stems resisting rotation during testing. For this reason, a shorter rotation arm was designed which enabled stems to be cut off nearer ground level in order to minimise their influence during measurements (Plate 4.2.2). Secondly, the primary use of the torquemeter was to provide accurate measurements of the strength of the root system for the root component of the model. For this reason, the torquemeter was set to display the maximum force during rotation rather than the resting force after rotation. It should be noted that to use the device in the MT95 experiment, it was necessary to artificially wet the soil with the equivalent of 40 mm water, due to such dry soil conditions. The water was allowed to soak in for 4 h before testing. Calculation of the overall root anchorage strength is given by the method of Crook & Ennos (1993) and requires the root cone diameter as described above.

4.2.6 Soil measurements

The following soil measurements were taken at close proximity to the plants (i.e. as near to the roots as possible without harming the root structure) at each time ten plant samples were taken.

Soil shear strength was measured using a shear vane with a 19 mm blade diameter, at 2.5 cm and 5.0 cm depths below the soil surface. The shear vane was pushed into the soil to the required depth and the torque recorder was rotated at a constant speed and the torque required to shear the soil was recorded (ADAS, 1982). Ten measurements of shear strength were taken at each depth, in each plot.

Soil moisture content was measured in the laboratory using the following technique: the soil was sieved to remove any stones or plant material, weighed, and then oven dried at 100°C for 16 h or until it reached constant weight. Dry weight was then recorded to enable moisture content to be calculated (ADAS, 1982). Soil moisture content was measured in conjunction with measurements of natural frequency, root resistance (torque-meter) and soil strength in July. Soil samples for moisture were taken at 2.5 and 5.0 cm depths, using ten small cores per plot, taken from the areas tested for soil shear strength. Soil moisture content was also measured using Time-Domain Reflectometry (TDR) (Nielsen *et al.*, 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. 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. Four plots were monitored by the TDR probes (four 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.

4.2.7 Other model specific measurements

Table 4.4 below shows the important aerodynamic and site parameters which are used in the model. Most fixed values were found from previous research, the sources of which are also shown. Most fixed parameter values were determined by Baker (1995) or from site data from the experiments at ADAS Rosemaund. The remaining values were obtained from other workers. Ear drag coefficient (C_D) is determined by ear size and peduncle length, and Graham (1983) presented a substantial amount of data for this parameter which can be used in any lodging wind speed calculation. Turbulence intensity (^xLv) is determined by crop surface roughness or varied shoot height. Finnigan (1979a) presented data for this parameter which were adequate for the calculations required. Finally, an observation time (T) of one hour was used from the work of Gardiner (1994).

Table 4.6 The standard aerodynamic and site parameters used in the model.

Model parameter	Value	Source
C_D	0.3	Graham (1983)
T (s)	3600	Gardiner (1994)
^xLv (m), σ/V	1.00, 0.50	Finnigan (1979a)
c, τ (sec), V_g (m/s), A (m^2)	0.05, 0.3, 14, 0.008	Baker (1995)
V_{99} (m/s), V_{50} (m/s), I_{50} (mm), H (m)	14, 4, 3, 100	Site meteorological data

4.2.8 Disease assessment

Visual assessments for common symptoms of eyespot (*Pseudocercosporella herpotrichoides*) and take-all (*Gaumannomyces graminis*) i.e. brown stem lesions

(ADAS, 1985) and blackened roots (ADAS, 1981), were carried out routinely whenever other measurements were taken. For the ST94 and MT95 trials, a full assessment of stem base diseases was carried out at GS 87 on all plots. For the MT94 trial, only a subset of 24 plots (which were extensively monitored) was assessed for disease.

4.2.9 Environmental measurements

Rain and wind speed were measured by an 'on-site' (within 10 m in MT94 and 50 m in MT95/MT96 of the centre of the trial) Delta-T portable weather station, see Plate 4.2.4 (Appendix 1). Rainfall (mm) measurements were recorded every 10 min in July, using a tipping bucket rain gauge attached to the weather station. A high resolution anemometer was used to sample and record wind speed (m/s) every 5 s during July. Average wind speeds were calculated from these frequent readings using Delta-T View software. A wind vane was used to record wind direction (°).

4.2.10 Video recording

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, see Plate 4.2.3 (Appendix 1). When windy or wet weather conditions were forecast, the camera was put into its waterproof housing and set up on the tripod in a high lodging risk plot, and left to record crop movement with the aim of recording lodging events.

4.2.11 Lodging and leaning assessment

When lodging was observed, assessments of its severity were made using the following scale (partly derived from the method of Caldicott & Nuttall (1979)):

% crop area upright (crop at an angle up to 4^{o} from the vertical);

% crop area leaning (crop leaning between 5^{o} and 44^{o} from the vertical);

% crop area lodged (crop lodged between 45^{o} and 90^{o} from the vertical);

% crop area lodged flat (severe lodging).

During lodging assessments, the dominant mechanism and point of failure was identified and noted i.e. whether by stem failure due to mechanical buckling, root failure or other causes (e.g. disease or animal damage). Plots were assessed by walking along the length of the plot and assessments were carried out on the plot harvest areas but not the plot sampling areas. When scoring plot lodging, the outside three rows of each plot were not assessed in order to reduce the 'edge effects' created by plot structure. The lodging score will, therefore, more accurately reflect what happens in a whole field situation.

4.2.12 Measurements' schedule for lodged plots

An area of 4 x 10 m^2 was left unsampled for lodging to be assessed. The three outer rows of each plot were not scored in order to eliminate the 'edge effect'. After a lodging event, % area of plot upright, leaning, lodged and lodged flat was scored. Lodging scores continued at a minimum of weekly intervals thereafter. The point of failure was identified as soon as possible after a lodging event, and photographs and/or VCR film were used to provide visual close-up detail of the soil-root-stem base area where lodging originated. As soon as possible after lodging occurred, ten plants (including roots) were pulled up at random from lodged areas of the plot. This was repeated for ten plants in unlodged areas of the plot. Before each plant was pulled up, soil shear strength was measured close to the plant and a small soil core was taken for measurement of soil moisture content. Plant measurements performed in the laboratory included total plant fresh weight, plant height, ear area, centre of gravity, plant shoot number, stem diameter, stem wall width, stem strength, crown root number, root cone diameter and structural rooting depth.

4.2.13 Statistical analysis

Where tabulated results have been statistically analysed using analysis of variance (Genstat 5), they are presented with the residual degrees of freedom (df), the standard error of the mean (SEM), the probability (p-value), the coefficient of variation (CV%) and the least significant difference (LSD). All LSDs were calculated at the 5% significance level.

5. RESULTS : THE FIELD EXPERIMENTS

Section 5.1 provides a summary of the weather and overall crop performance from the experimental work which took place over all three experimental seasons; 1993-94, 1994-95 and 1995-96. Sections 5.2, 5.3 and 5.4 present results from the field experiments which relate specifically to the model, and are primarily aimed at investigating the effects of different agronomic treatments on components of lodging risk. The results were all obtained in the period between June and August (with the exception of stem base characters which were measured in May). It should be noted that, although the details of the MT96 experiment are described in the Materials & Methods chapter, no field results are presented for MT96 in Sections 5.2, 5.3 and 5.4. This is because time constraints prevented full analysis of these data, which were collected coincident with the writing of this thesis. The main reason for including the MT96 experiment, was that this included a series of lodging events which occurred during that season. Lodging scores from these lodging events have been analysed and discussed later in this chapter (section 5.6).

5.1 Crop performance

5.1.1 *Weather conditions*

Rainfall (Fig. 5.1) was well above average over autumn (which delayed drilling) and winter 1993-94. Air temperatures and sunshine hours were also on the whole below average for this period which also impeded crop growth. 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 compared to the 20-year long term mean (LTM) of 98 mm for both months). For 1993-94 and 1994-95 seasons (Fig. 5.2), average daily wind speeds 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 (Figs 5.3 & 5.4). Similar rainfall patterns occurred in 1994-95 (Fig. 5.1) as in the previous season, with high rainfall over winter, but weather was dry through the spring and summer. June and July 1995 were extremely dry with only 12 mm and 6 mm compared to LTMs of 50 mm and 48 mm respectively.

For the 1995-96 season, rainfall patterns (Fig. 5.1) were different from the two previous seasons, with average rainfall overwinter, but above average rainfall in February, March and April. Although rainfall in May, June and July was below average, the soil was still much wetter from early June onwards than in the previous seasons, due to high rainfall in late spring. Wind speeds (Fig. 5.2) were also below average during June and July in 1996.

5.1.2 *Crop establishment*

Difficult drilling conditions in autumn 1993 caused sowing dates later than intended, and the poor seedbed in combination with a wet autumn caused poor plant establishment (Table 5.1). Both the high and low seed rates established poorly with 24-56% establishment. In terms of plant numbers, the high seed rate only resulted in a plant number equivalent to that intended for the low seed rate, with 197-225 plants/m^2. In terms of plant density, it was therefore considered that the range of agronomic treatments were towards the low end of the lodging risk scale. For those reasons, it was decided to impose all the treatments as planned but not to monitor the low seed rate plots intensively. At a slightly later stage, it was also decided to discontinue monitoring the factorial autumn residual nitrogen treatment because there were no visible differences (in terms of height, greenness etc.) between plots which received autumn nitrogen at 80 kg/ha and plots which did not. An analysis of soil mineral N confirmed that relatively small differences existed between plots, probably due to the wet autumn and winter causing nitrate leaching below the depth of root uptake.

Table 5.1 Crop establishment for the MT94 experiment.

Sowing date	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).

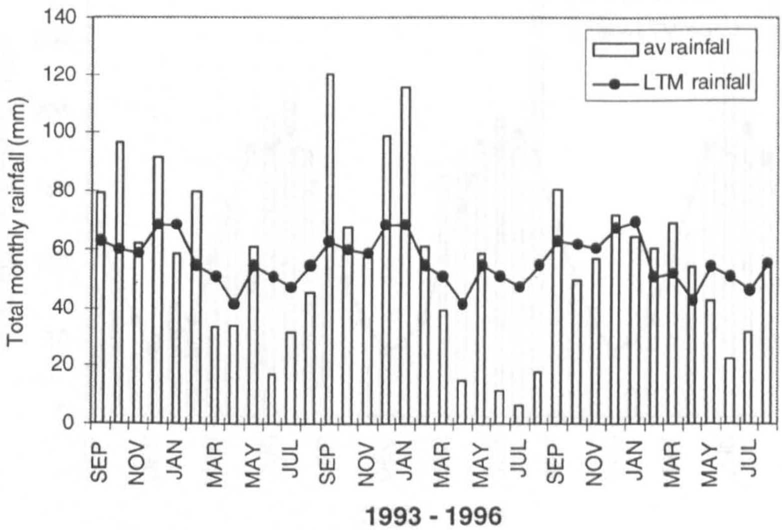

Fig 5.1. Total monthly rainfall vs. LTM at ADAS Rosemaund (1993-96).

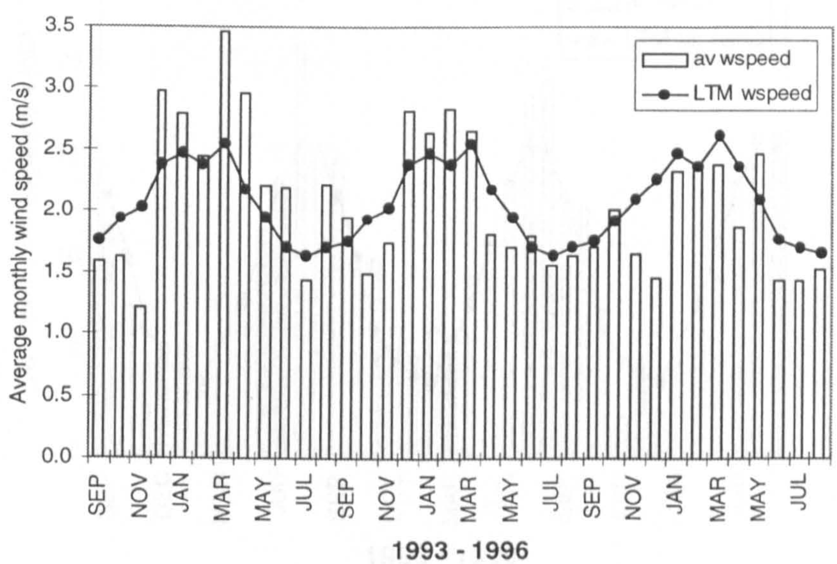

Fig 5.2. Average monthly wind speed vs. LTM at ADAS Rosemaund (1993-96).

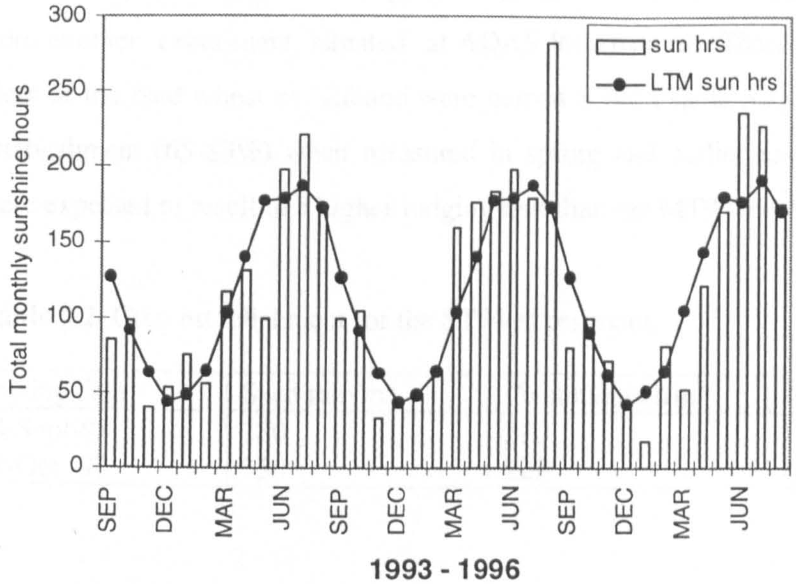

Fig 5.3. Total monthly sunshine hours vs. LTM at ADAS Rosemaund (1993-96).

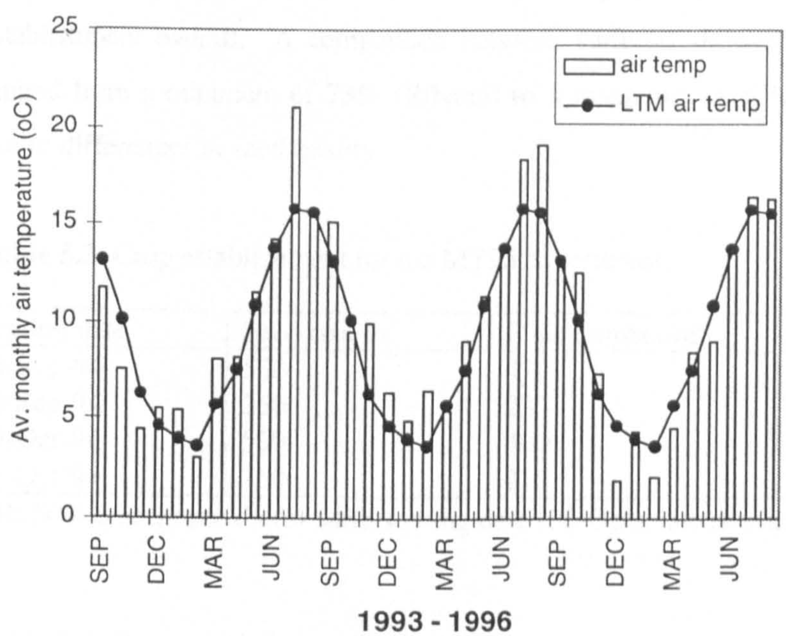

Fig 5.4. Average monthly air temperature vs. LTM at ADAS Rosemaund (1993-96).

In an attempt to increase the range of lodging risk in the study, plots were utilised from another experiment situated at ADAS Rosemaund. These 24 supplementary plots of the feed wheat cv. Riband were named ST94 (Table 5.2). They had better establishment (65-83%) when measured in spring and earlier sowing dates, which were expected to result in a higher lodging risk than the MT94 experiment.

Table 5.2 Crop establishment for the ST94 experiment.

Sowing date	Seed rate/m^2	Plant number/m^2	% establishment
24-Sept-93	350	290	83
17-Oct -93	350	229	65

In autumn 1994, better drilling conditions and a good seedbed led to good establishment in MT95 at both sowing dates and seed rates, creating contrasting plant densities, as intended (Table 5.3). The VT95 experiment also showed good plant establishment overall. A comparison between varieties showed that establishment ranged from a minimum of 73% (Riband) to a maximum of 82% (Florin), possibly due to differences in seed quality.

Table 5.3 Crop establishment for the MT95 experiment.

Sowing date	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

NB: 50% emergence dates: early sowing date (06-Oct); late sowing date (04-Nov).

Table 5.4 Crop establishment for the MT96 experiment.

Sowing date	Seed rate/m^2	Plant number/m^2	% establishment
20-Sep-95	500	446	89
20-Sep-95	250	244	98
01-Nov-95	500	326	65
01-Nov-95	250	158	63

In the MT96 experiment, both early sown, high and low seed rate crops established well (Table 5.4). 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.

5.1.3 *Crop growth*

To provide a general picture of overall crop growth in each season, this section, gives results for just the two treatments expected to give the most contrast. In the MT94 experiment, because low seed rate and low residual nitrogen treatments were not intensively monitored, only a sowing date difference could be compared (1HN1 vs. 2HN1). Where differences are quoted in the text, these were significant at the 5% level of probability.

In MT94, above-ground dry matter was similar for both sowings throughout the season. Both the early and late sown crops accumulated more than 18 t/ha dry matter by harvest (Fig. 5.5a). Above-ground fresh weight, which was expected to be important in terms of lodging risk, increased rapidly through May for both the early and late sown crops (Fig. 5.5b). However, by early July, the canopy of the early sown crop had a significantly larger fresh weight (70 t/ha) than that of the late sown crop (55 t/ha). Shoot number and GAI were not significantly different throughout the season although during late spring, the early sown crop did have a greater shoot density than the late sown crop (Figs 5.5c & 5.5d). The 1HN1 and 2HN1 treatments yielded 10.37 t/ha and 11.07 t/ha respectively. Two similar treatments (which only differed through sowing date) were also compared for the ST94 trial. Initially through the spring they were very similar, but by early July, the early sown crop (14.6 t/ha) had accumulated significantly more dry matter than the late sown crop (13.1 t/ha), see Fig. 5.6a. As in MT94, the fresh weight of the late sown crop's canopy in ST94 declined sooner and in early July was significantly less (48.5 t/ha) than that of the early sown crop (73.1 t/ha), see Fig. 5.6b. By July, shoot number was not significantly different between the early and late sown crops, see Fig. 5.6c. From early spring through to the end of May, the early sown crop had a larger GAI than the late sown crop. By GS 39, GAIs were 7.4 and 6.2 respectively (Fig. 5.6d). The early and late sown crops yielded 11.10 t/ha and 10.73 t/ha respectively.

For the MT95 experiment, the two treatments selected for comparison through the season contrasted in both sowing date, seed rate and residual nitrogen level. The treatments selected to represent a high and low expected lodging risk respectively were 1HN1 and 2LO1. The high risk treatment appeared to accumulate more dry matter and a larger canopy fresh weight throughout the season than the low risk treatment, but these were not significantly different (Figs 5.7a & 5.7b). During early spring the high risk treatment had approximately 100 more shoots/m^2 than the low risk treatment, but good spring growth produced very similar shoot numbers in early summer (Fig. 5.7c). The high risk treatment had a significantly greater GAI (6.6) than the low risk treatment (4.9) by mid May, and this difference persisted through until July (Fig. 5.7d). The 1HN1 and 2LO1 treatments yielded 8.57 t/ha and 9.95 t/ha respectively.

For the VT95 trial, measurements of crop performance such as biomass and GAI were not recorded through the season, but an assessment of above-ground dry matter and shoot number was carried out at GS 65 (Table 5.5). From the subset of six varieties, Cadenza had the greatest above-ground dry matter and Beaver had the highest shoot number/m^2. Both these varieties had moderate to low standing power (NIAB, 1995). No statistics were available for the VT95 results because replicates were not measured separately.

Table 5.5 Crop biomass and shoot number at GS 65 for the VT95 experiment.

Variety	Above-ground DM (t/ha)	Shoot number/m^2
Beaver	14.5	527
Cadenza	15.4	492
Hereward	14.0	494
Little Joss	14.8	458
Mercia	13.2	522
Riband	13.9	414

For the MT96 experiment, the treatments compared (1HN1 vs. 2LO1) were the same as in MT95. The early sown, high seed rate, high residual N crop initially built up much greater dry matter (Fig. 5.8a) through the season, but through the summer, the late sown, low seed rate, low residual N crop produced dry matter at a much faster rate, and reached nearly 20 t/ha by harvest. The early season difference in crop growth between the two treatments could be seen even more clearly for above-ground fresh weight (Fig. 5.8b). The 1HN1 crop had built up about 60 t/ha of above-ground fresh weight by the beginning of June (nearly twice as much as the 2LO1 crop), producing a very heavy canopy during the expected period of lodging risk. The 1HN1 treatment initially had about 500 more shoots/m^2 than the 2LO1 treatment in spring (Fig. 5.8c). However, from the end of May, when shoot number had steadied in 2LO1, shoot number in 1HN1 continued to decline until harvest, when both treatments had about 750 shoots/m^2. A possible reason for the decrease in shoot number could be the severe early season lodging that occurred in the 1HN1 crop. Finally, the 1HN1 crop had a total GAI of over 10 by full canopy expansion (GS 39), compared to a much smaller GAI of just over 6 for 2LO1 (Fig. 5.8d). The 1HN1 and 2LO1 treatments yielded 8.12 t/ha and 10.31 t/ha respectively.

In summary, crop performance results in the 1993-94 season showed little variation in growth due to the sowing date difference. More variation occurred in the 1994-95 season, although the late sown treatments yielded much better than expected compared to the early sowing, an unusual result (Fielder, 1988). Large variation in crop growth between contrasting treatments was achieved in the 1995-96 season, which was more in line with expectations.

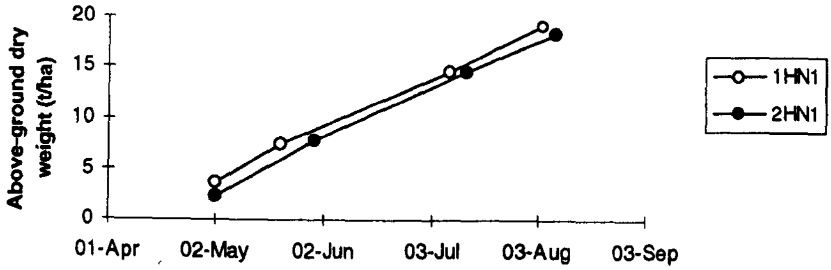

Fig 5.5a

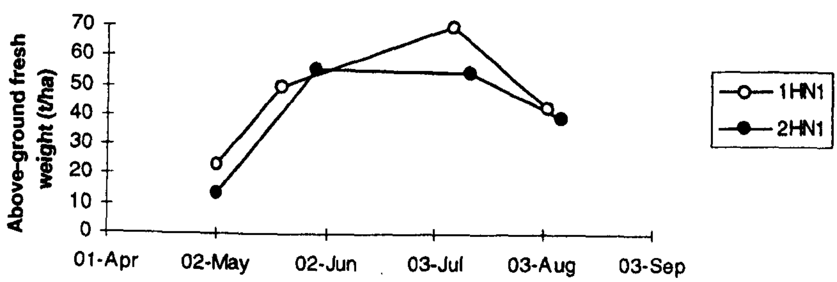

Fig 5.5b

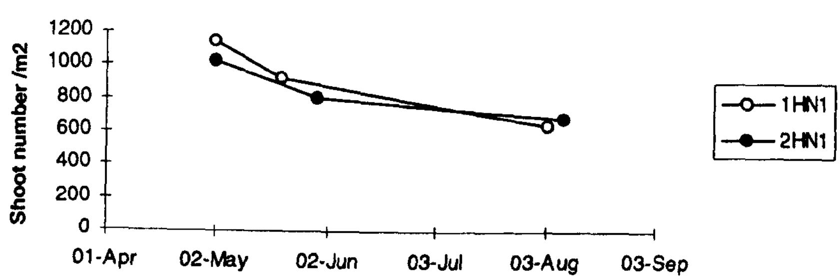

Fig 5.5c

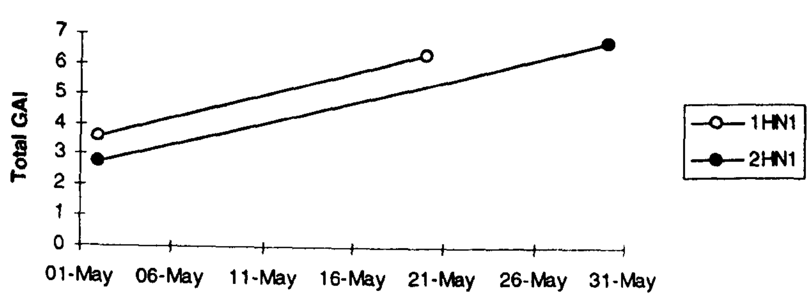

Fig 5.5d

Fig. 5.5. **(a)** Above-ground dry weight, **(b)** above-ground fresh weight, **(c)** fertile shoot number and **(d)** total green area index with time for the MT94 experiment.

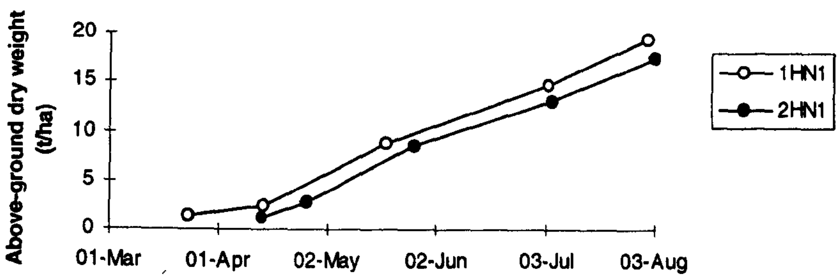

Fig. 5.6a

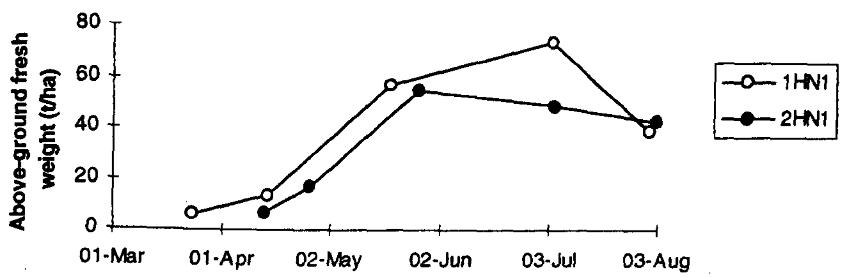

Fig. 5.6b

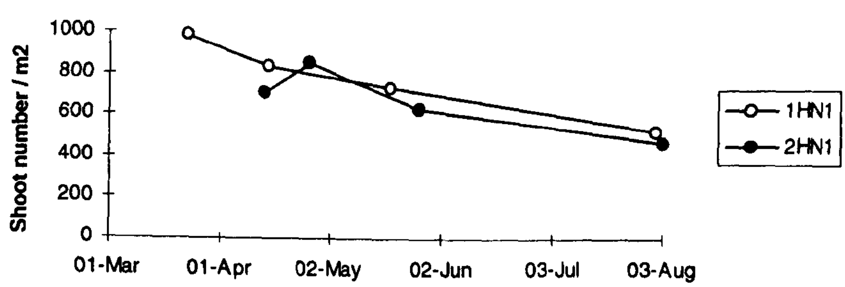

Fig. 5.6c

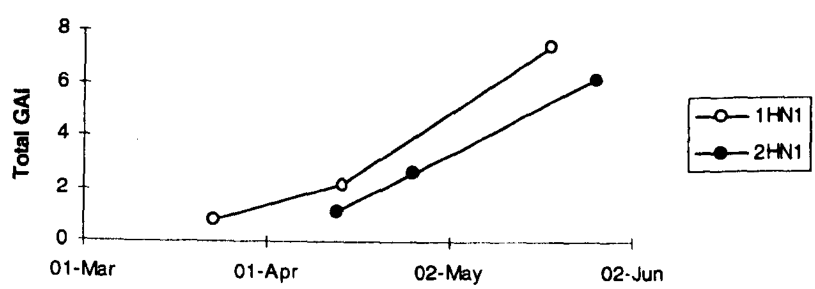

Fig. 5.6d

Fig. 5.6. (**a**) Above-ground dry weight, (**b**) above-ground fresh weight, (**c**) fertile shoot number and (**d**) total green area index with time for the ST94 experiment.

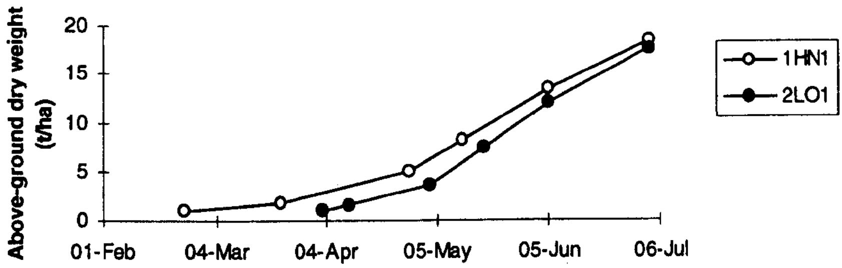

Fig. 5.7a

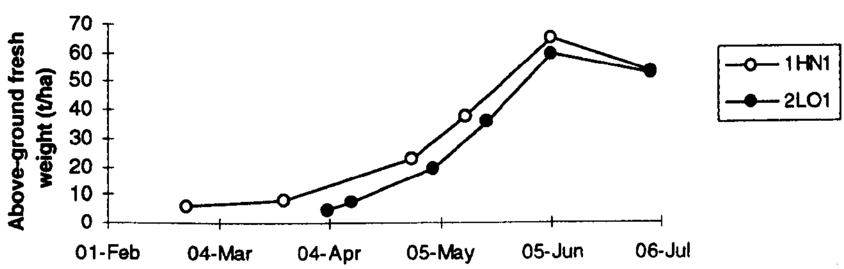

Fig. 5.7b

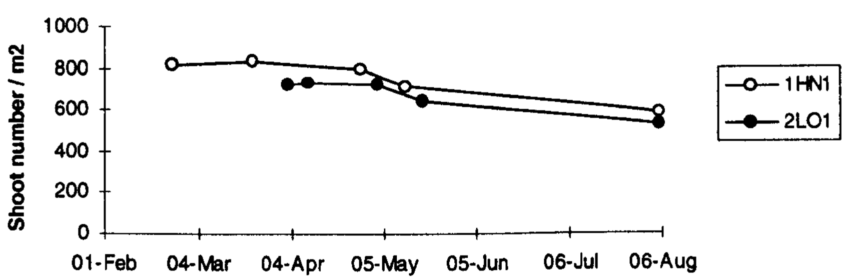

Fig. 5.7c

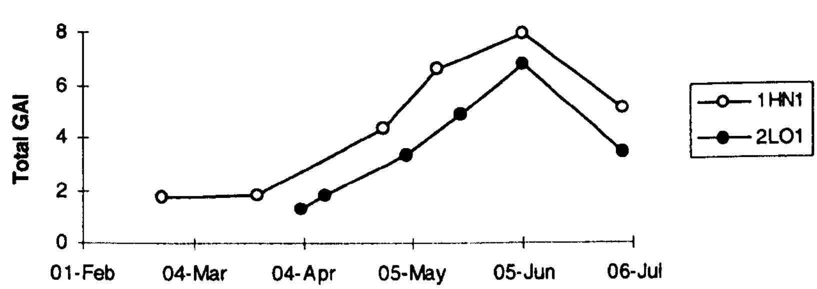

Fig. 5.7d

Fig. 5.7. **(a)** Above-ground dry weight, **(b)** above-ground fresh weight, **(c)** fertile shoot number and **(d)** total green area index with time for the MT95 experiment.

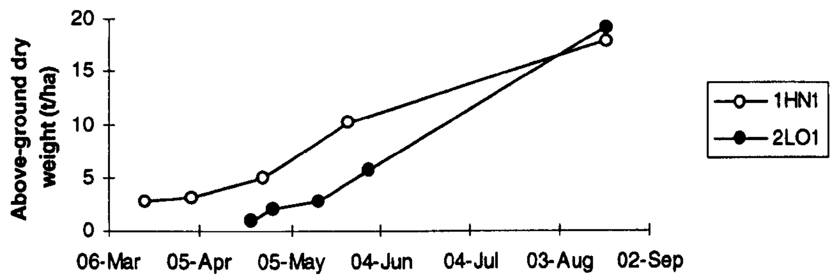

Fig. 5.8a

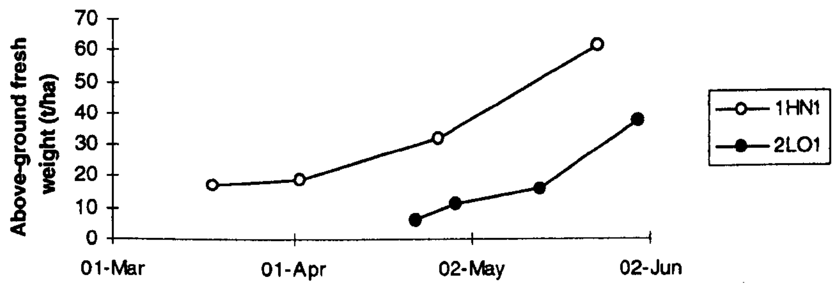

Fig. 5.8b

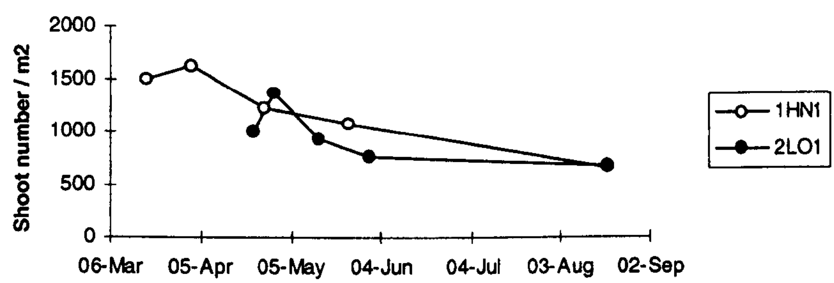

Fig. 5.8c

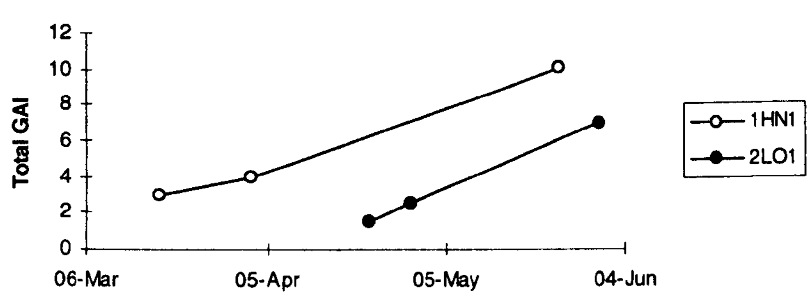

Fig. 5.8d

Fig. 5.8. **(a)** Above-ground dry weight, **(b)** above-ground fresh weight, **(c)** fertile shoot number and **(d)** total green area index with time for the MT96 experiment.

5.1.4 *Stem base disease assessment*

For MT94, true eyespot infected 20-30% of stems, the earlier sowing date showing more infection than the late sowing date. Sharp eyespot was only present in very small amounts, infecting between 1-5% of stems. Similar levels of stem base disease occurred in ST94 as in MT94, with the earlier sowing date again showing more true and sharp eyespot.

In the MT95 experiment, internodal fusarium was quite frequent, treatments showing 6-33% stems infected. The early sowing date and high seed rate showed significantly more infection than the late sowing date and low seed rate. Application of PGRs significantly reduced Fusarium infection, probably due to thickening of the stem wall. Sharp eyespot was less prevalent than Fusarium in nearly all treatments and the early sown treatments again showed significantly more infection than the late sown treatments. Disease incidence in the VT95 trial was relatively low. Within the subset of six varieties which were more intensively monitored, Beaver had the most true eyespot (17%) and Riband had the least (8%).

In the MT96 experiment, the amount of stem base disease was very low in all treatments. As a result, an assessment of stem base disease was not carried out.

5.1.5 *Late-season soil conditions*

In the 1993-94 season, soil conditions in July and early August were generally dry. In the ST94 experiment, soil strengths averaged 65-100 kPa in the top 50 mm of soil. In the MT94 experiment, high soil strengths were reduced to between 20-30 kPa (top 50 mm soil) by pre-harvest rain showers.

In the 1994-95 season, soil conditions in the MT95 experiment during July were drier than the previous season. Soil strength was measured weekly from May onwards in two different treatments (30 shear vane measurements per treatment). By the end of June, soil strength averaged 94-104 kPa at a depth of 25 mm and 108-115 kPa at a depth of 50 mm (8-11% soil moisture). With only 6 mm of rain in July, soil strength continued to increase through July and values exceeded the maximum of the shear vane (120 kPa). Estimates using the ADAS Irriguide System (Bailey & Spackman, 1996) showed that the soil moisture deficit (SMD) under winter wheat at ADAS Rosemaund was greater than 105 mm from 7 June until harvest (when it had reached 155 mm) in 1995. For the silty clay loam soil type at Rosemaund, an SMD of 105 mm represents 50% of the available water capacity (AWC), with the total AWC calculated at 210 mm for Rosemaund. It is estimated that once soil moisture becomes less than 50% AWC the crop becomes water stressed. The SMD curve showed that the crop was probably water stressed for the whole 'lodging risk' period (June and July) in 1995. No results have been presented from TDR measurements of soil moisture fluctuations during July, because July had extremely low rainfall in both monitored seasons (1993-94 and 1994-95), resulting in dry soil and few useful results.

In the 1995-96 season, soil conditions in the MT96 experiment were fairly dry, but much more variable than in the two previous seasons, due to several falls of rain during June, July and early August. Soil strengths in early July averaged 50 kPa at 25 mm depth and 85 kPa at 50 mm depth. However, soil strengths measured immediately after root lodging events (all associated with rainfall), averaged between 20-25 kPa, with individual plot values as weak as 15 kPa.

5.1.6 *Grain yields and grain quality*

For MT94, only the lodging control treatments significantly affected grain yields (Table 5.6), with the canopy management G5 treatment producing between 1.5-2.0 t/ha less yield than the NIL or 5C and 5C+T (PGR) treatments.

Table 5.6 Grain yields for the MT94 experiment.

	Treatment means			
	NIL	5C	5C+T	G5
Yield (t/ha) 85% DM	11.02	10.98	11.20	9.38
Grand mean 10.65	**SEM**	**p-value**	**CV%**	**LSD**
Yield (56df)	0.182	<0.001	8.4	0.514

NB: Sowing date, seed rate and residual nitrogen did not significantly affect yield.

Grain quality measurements (as treatment means) for MT94 (Table 5.7) showed that the G5 treatment had a significantly greater TGW than the NIL and PGR control treatments. The G5 and NIL 'control' also had significantly greater specific weights than the PGR treatments. Finally, the late sowing date had a significantly smaller weight of grain per ear than the early sowing date.

Table 5.7 Grain quality measurements at harvest for the MT94 experiment.

Treatment	TGW (g)	Grain weight (g/ear)	Specific weight (g)
NIL	43.7	-	82.7
5C	42.6	-	80.4
5C+T	41.6	-	80.9
G5	46.8	-	82.4
TOS 1	-	1.83	-
TOS 2	-	1.66	-
SEM	1.00	0.026	0.39
p-value	<0.05	<0.05	<0.001
CV%	5.6	2.6	2.4
LSD	3.09	0.159	1.10
(df)	(12)	(2)	(59)

For the ST94 experiment, agronomic control (sowing date and lodging control treatments) did not significantly affect harvest yields, therefore treatment means are not presented. The grand mean yield was 10.97 t/ha for the cv. Riband.

Table 5.8 Grain quality measurements at harvest for the ST94 experiment.

Treatment	TGW (g)	Grain weight (g/ear)	DMHI %
NIL	46.4	2.12	49.6
5C	46.0	2.26	51.2
5C+T	44.0	2.16	51.9
G5	51.3	2.50	54.5
SEM	0.10	0.085	0.88
p-value	<0.01	<0.05	<0.05
CV%	5.2	9.2	4.2
LSD	3.08	0.261	2.71
(12df)			

Grain quality measurements for ST94 (Table 5.8) showed that the G5 treatment had significantly higher TGWs and grain weights per ear than the other lodging control treatments. G5 also had a significantly greater harvest index than the NIL and 5C PGR, but was not significantly different from the 5C+T PGR.

The mean grain yield for MT95 was 9.56 t/ha at 85% dry matter which is above average for the cv. Mercia. The analysis of variance of MT95 yields showed a significant three-way interaction between seed rate, residual nitrogen and lodging control treatments (Table 5.9). With a high seed rate and low residual nitrogen, yields were significantly better with no PGR (9.75 t/ha) than the high seed rate, high residual nitrogen and no PGR combination (8.95 t/ha). This yield difference was probably due to lodging in the 1HN1 treatment.

Table 5.9 The effect of seed rate, residual nitrogen (ResN) and lodging control on grain yield (t/ha at 85% DM) in the MT95 experiment.

Lodging control treatment	HSR High ResN	HSR Low ResN	LSR High ResN	LSR Low ResN
NIL	8.95	9.75	9.68	9.77
5C	9.64	9.66	9.57	9.58
5C+T	9.95	9.64	10.12	9.89
G5	9.58	8.90	9.25	9.13
Grand mean 9.56	**SEM**	**p-value**	**CV%**	**LSD**
Yield (56df)	0.140	<0.05	3.6	0.369

The following results relate to main agronomic effects alone. Yield was not significantly affected by sowing date, probably because the later sown crop grew away well in the spring and rapidly caught up with the early sown crop. Residual nitrogen levels alone had no significant effect on final yield, probably because differences were counteracted by proportional adjustments to fertiliser N according to the mineral N status of the soil in the spring. The low residual nitrogen treatment received more fertiliser in the spring than the high residual nitrogen treatment. Seed rate did not significantly affect yield probably because the low seed rate had very good establishment and generated similar shoot numbers by harvest to the high seed rate. The lodging control treatments did significantly affect yield, but the PGR programmes tended to give greater yields. The G5 treatment gave lower yields, apparently due to the inefficiency of the late nitrogen application in drought conditions. This was supported by differences in performance of G5 treatments between replicates. One replicate block was positioned on deeper, more moisture retentive soil and G5 yields were relatively better.

Table 5.10 Effect of an interaction between sowing date, seed rate and residual nitrogen on grain quality at harvest in the MT95 experiment.

a) Thousand grain weight (g).

Residual nitrogen treatment	TOS 1		TOS 2	
	HSR	LSR	HSR	LSR
30-ResN	44.5	44.0	45.0	45.4
330-ResN	41.5	42.9	43.2	42.9
(56df)	**SEM**	**p-value**	**CV%**	**LSD**
TGW	0.36	<0.05	2.9	1.34

b) Specific weight (g).

Residual nitrogen treatment	TOS 1		TOS 2	
	HSR	LSR	HSR	LSR
30-ResN	81.4	81.4	82.5	82.5
330-ResN	80.7	81.3	82.6	82.3
(56df)	**SEM**	**p-value**	**CV%**	**LSD**
Specific weight	0.12	<0.01	0.5	0.94

In the MT95 experiment, both TGW and specific weight (SPWT) were affected by interactions between sowing date, seed rate and residual nitrogen (Table 5.10a,b). The interaction showed that high residual N significantly reduced TGW of high seed rate crops at both sowing dates. Furthermore, the early sown, high seed rate, high residual N crop had a significantly smaller TGW than the equivalent late sown treatment. For SPWT, the interaction showed that for both levels of seed rate and residual N, it was significantly less in the early sown crop. Also in the MT95 experiment, the G5 treatments produced significantly greater TGWs (p<0.01) and SPWTs (p<0.01) than the other lodging controls, at both levels (and all combinations) of seed rate and residual N.

The late sown crop produced a significantly higher dry matter (DM) harvest index (Table 5.11), and full rate PGR (5C+T) produced a significantly higher DM harvest index than the NIL 'control'. The G5 treatment produced the highest DM harvest index (49.7%), significantly greater than all other lodging control treatments.

Table 5.11 Effect of sowing date and lodging control on dry matter harvest index (DMHI) in the MT95 experiment.

Sowing date	TOS 1	TOS 2		
DMHI (%)	47.4	48.4		
Lodging control	NIL	5C	5C+T	G5
DMHI (%)	46.5	47.5	48.0	49.7
(df)	**SEM**	**p-value**	**CV%**	**LSD**
Sowing date (2)	0.17	<0.05	0.6	1.04
Lodging control (56)	0.41	<0.001	4.1	1.16

Yields and grain quality measurements for the subset of six varieties in VT95 are shown in Table 5.12. Unanalysed meaned data was provided by ADAS Rosemaund for this trial. The yield of Little Joss was relatively small compared to the other varieties, probably due to a much smaller harvest index ratio and some yield loss due to lodging. As a result, Little Joss also had the smallest TGW of the six varieties.

Table 5.12 Grain yields and grain quality measurements for the VT95 experiment.

Variety	Yield (t/ha)	DMHI (%)	TGW (g)	SPWT (g)
Beaver	9.48	50.8	46.2	77.0
Cadenza	9.87	48.7	48.2	80.0
Hereward	8.63	49.6	43.8	83.1
Little Joss	5.41	34.5	41.6	81.1
Mercia	8.70	49.1	42.8	80.5
Riband	8.47	52.4	45.5	76.3

In the MT96 experiment, yields were affected by a three-way interaction between sowing date, residual nitrogen and lodging control (Table 5.13). Yield of the NIL lodging control with high residual N, was significantly lower (8.77 t/ha) in the early sown crop than in the late sown crop (10.06 t/ha). In all cases (except for 1HN1), the application of PGRs did not significantly increase yield compared to the NIL 'control', and yields of treatment combinations with the G5 lodging control were in nearly all cases significantly lower than other treatments. Seed rate did not significantly affect yield even as a main effect alone although, a trend showed the low seed rate yielded slightly more than the high seed rate. Grain quality in the MT96 experiment was affected by interactions between sowing date and lodging control, and between residual nitrogen and lodging control (Table 5.14). Specific weight was significantly less for the early sown NIL and G5 lodging control treatments. PGR treatments were not significantly different between sowing dates and did not significantly increase specific weight compared to the NIL 'control'. Both TGW and DM harvest index were on average higher for the later sowing date (42.7 g and 54%) than the earlier sowing date (38.8 g and 46%).

Table 5.13 The effect of seed rate, residual nitrogen (ResN) and lodging control on grain yield (t/ha at 85% DM) in the MT96 experiment.

Lodging control treatment	HSR High ResN	HSR Low ResN	LSR High ResN	LSR Low ResN
NIL	8.77	9.97	10.06	10.20
5C	10.07	10.30	9.98	9.91
5C+T	9.57	9.90	9.70	10.13
G5	9.11	8.82	9.09	9.69
Grand mean 9.70	**SEM**	**p-value**	**CV%**	**LSD**
Yield (56df)	0.150	<0.001	3.8	0.438

Table 5.14 The effect of agronomic control on specific weight (g) grain quality in the MT96 experiment.

Treatment	NIL	5C	5C+T	G5
TOS 1	82.6	82.5	82.6	80.7
TOS 2	83.5	83.0	82.8	82.7
50-ResN	83.1	82.7	82.9	81.5
350-ResN	83.0	82.8	82.6	81.8
(56df)	**SEM**	**p-value**	**CV%**	**LSD**
TOS.lodging control	0.13	<0.001	0.5	0.77
Residual N.lodging control	0.13	<0.05	0.5	0.35

With lodging occurring across many treatments in the MT96 experiment, it was expected that the earlier, and more severely lodged treatments would have reduced grain quality through reduced Hagberg Falling Numbers (HFN). However, results showed no significant differences between any of the agronomic treatments imposed, with a grand mean HFN of 342 for the experiment.

5.2 Canopy characteristics

5.2.1 *Natural frequency*

The following crop characteristics are expected to influence the natural frequency of the plant, at the time of main lodging risk. Their possible determinants are shown in brackets :

- canopy weight (sowing date, seed rate, residual N, lodging control, recent rainfall)
- shoot density (seed rate, residual N), see section 5.2.3
- ear weight and area (variety, seed rate, residual N)
- stem length (sowing date, residual N, lodging control)
- stem diameter and weight per unit length (seed rate, residual N, lodging control), see section 5.3.1
- soil strength (rainfall, soil texture and structure)

Table 5.15 The effect of lodging control on stem length and ear weight at GS 72 in the MT94 experiment.

Treatment	Stem length (m)	Ear dry weight (g)
NIL	0.835	1.17
5C	0.734	1.04
5C+T	0.728	1.11
G5	0.877	1.39
SEM	0.0171	0.074
p-value	<0.001	<0.05
CV%	5.3	15.5
LSD (12df)	0.0526	0.229

In the MT94 experiment (Table 5.15), the NIL and G5 treatments were significantly taller than the 5C and 5C+T PGR treatments at GS 72. Full PGR (5C+T) shortened height by just over 10 cm (13%) compared to the NIL 'control' treatment. Sowing date did not significantly affect stem length at GS 72 although the early sown crop was slightly taller. G5 had significantly more dry weight per ear than all other treatments for both sowing dates (with the exception of the early sown NIL 'control'). No such difference occurred for ear fresh weight at GS 72, although G5 did have a greater ear fresh weight for both sowing dates. Above-ground fresh weight was not significantly affected by sowing date at GS 72, although the earlier sown crop tended to have a greater canopy fresh weight overall. The G5 treatment (45.7 t/ha) had a significantly lower canopy fresh weight than all other lodging control treatments (av. 65.5 t/ha).

Table 5.16 The effect of sowing date and lodging control on stem length (m) at GS 72 in the ST94 experiment.

Treatment	NIL	5C	5C+T	G5
TOS 1	0.875	0.788	0.792	0.827
TOS 2	0.752	0.737	0.743	0.667
(12df)	**SEM**	**p-value**	**CV%**	**LSD**
Stem length	0.0123	0.001	2.8	0.0366

All early sown treatments in the ST94 experiment (Table 5.16) were significantly taller than later sown treatments (as expected) by 12% on average. PGR lodging control treatments only reduced length significantly for the early sown crop, by 10%, compared to the NIL 'control'. However, the late sown G5 treatment was significantly shorter than the early sown G5 treatment, and this appeared to be attributable to an affect on length of internode 4. Ear fresh weight was not significantly affected by sowing date in the ST94 experiment, although the early sown crop produced heavier ears. Above-ground fresh weight was significantly greater in the early sown crop at GS 72.

Table 5.17 The effect of agronomic treatments on crop height (m) at GS 87 in the MT95 experiment.

Treatment	NIL	5C	5C+T	G5	330-ResN	30-ResN
TOS 1	0.990	0.904	0.832	0.912	0.907	0.912
TOS 2	1.036	0.912	0.834	0.991	0.952	0.934

(56df)	**SEM**	**p-value**	**CV%**	**LSD**
TOS.Lodging control	0.0061	<0.001	2.3	0.0174
TOS.Residual N	0.0043	<0.01	2.3	0.0124

In the MT95 experiment, interactions between sowing date and lodging control, and between sowing date and residual nitrogen occurred for crop height at GS 87 (Table 5.17); the late sown NIL and G5 treatments were significantly taller than the early sown NIL and G5 treatments. This appears to run counter to results at GS 69, where early sown crops had a higher centre of gravity than late sown crops. PGR treatments for both early and late sown crops reduced crop height by between 10-17 cm, for 5C and 5C+T, compared to the NIL 'control' crop. High residual nitrogen significantly increased crop height (by 2%) but only with the late sowing. Seed rate did not significantly affect crop height at GS 87.

A combination of early sowing, high seed rate and high residual nitrogen in MT95 produced a significantly greater total GAI ($p<0.05$) and total canopy fresh weight ($p<0.005$) at GS 59 than in the opposing treatments. There was 1 unit of GAI and 5 t/ha of fresh weight more than the late sown, low seed rate and low residual N crop. However, ear area or ear fresh weight were not significantly affected by the above treatment combinations at GS 59 or GS 72.

Table 5.18 The effect of lodging control on natural frequency at GS 87 in the MT95 experiment.

	NIL	5C	5C+T	G5
Natural frequency (Hz) dry weather	0.86	1.07	1.18	0.86
(56df)	**SEM**	**p-value**	**CV%**	**LSD**
Natural frequency	0.013	<0.001	6.3	0.037

In the MT95 experiment (Table 5.18), the NIL 'control' and G5 treatments had significantly lower natural frequencies than the PGR treatments (by 20-27%). This supports common experience which suggests that PGRs reduce lodging risk, in this case by causing an increase in natural frequency. Natural frequency was not significantly affected by sowing date, seed rate or residual N at GS 87.

It should be noted that the results in Table 5.19 below were obtained from a different experiment at ADAS Rosemaund, which used the varieties Brigadier and Soissons. The wetting treatments were applied according to the methodology in section 4.2.3, and ten plants were measured per replicate plot for each applied treatment. The wetting treatments significantly affected both soil shear strength and soil moisture. The extent of variation was large; soil moisture increased five-fold with 20 mm water applied and soil strength decreased by over three quarters. With 20 mm water applied artificially, plant natural frequency was significantly less (10%) than the 0 mm control treatment.

Table 5.19 The effect of soil wetting on natural frequency at GS 87 in an experiment at ADAS Rosemaund in 1995.

Treatment	Natural frequency (Hz)	Soil strength (kPa)	Soil moisture (%)
0 mm water	1.36	112	4
10 mm water	1.37	38	15
20 mm water	1.22	25	21
SEM	0.023	-	-
p-value	0.001	<0.001	<0.001
CV%	4.2	14.6	6.1
LSD (10df)	0.072	10.9	1.0

A more extensive wetting experiment was undertaken on two contrasting treatments in the MT95 experiment, and six different amounts of water were applied between 0 and 80 mm (section 4.2.3). Although soil moisture varied between 4 and 22% and soil strength varied between 30-100 kPa, no significant differences were found in natural frequency. This may indicate the importance of canopy wetting during rainfall causing natural frequency to fall. In this case, wetting treatments were allowed to soak into the soil before frequency was tested, by which time the canopy was dry.

Results from the VT95 experiment (Table 5.20) showed that Little Joss and Cadenza were significantly taller, with lower natural frequencies than Riband, Hereward, Mercia and Beaver. Cadenza was on average about 14 cm taller than the other modern varieties, with a 0.19 Hz lower natural frequency. With these large extremes in height, natural frequency under dry conditions (with no PGR applied) ranged from approximately 0.5-1.0 Hz. The high yielding varieties Hereward and Riband had the greatest ear area and fresh weight per ear, and the older variety Little Joss had the smallest. Little Joss, Beaver, Cadenza and Mercia all had significantly smaller ear areas than Riband.

Table 5.20 The effect of variety on canopy characteristics at GS 65 in the VT95 experiment.

Variety	Ear area (cm^2/ear)	Ear fresh weight (g/ear)	Crop height (m)	Natural frequency (Hz)
Hereward	9.28	2.02	0.846	0.96
Riband	9.90	2.19	0.882	0.93
Mercia	8.56	1.73	0.863	0.96
Cadenza	7.89	1.90	0.991	0.76
Beaver	7.41	1.90	0.833	0.93
Little Joss	5.32	1.35	1.523	0.56
SEM	0.315	0.088	0.0219	0.027
p-value	<0.001	<0.001	<0.001	<0.001
CV%	6.8	8.4	4.5	5.6
LSD	0.899	0.254	0.0618	0.078
(df)	(42)	(32)	(75)	(30)

Summary of natural frequency

For the variety Mercia, the extent of variation in natural frequency during late July was approximately 0.8-1.2 Hz. The extent of agronomic control was limited in MT95; however, lodging controls significantly altered frequency. It was expected that some variation in natural frequency would be caused by sowing date, seed rate or residual nitrogen. However, the 1994-95 season produced unusual growth patterns, most notably the later sowing date resulting in taller plants, and this may account for the absence of many agronomic affects on natural frequency. Variety also affects natural frequency with variation of 0.5-1.0 Hz at GS 65. Finally, wetting of the canopy and soil was shown to influence natural frequency although results were inconsistent.

5.2.2 *Centre of gravity*

The following crop characteristics are expected to influence height at the centre of gravity, and their possible determinants are shown in brackets :

- internode number (sowing date, variety)
- lower internode lengths (chlormequat, residual N)
- upper internode lengths ('Terpal', residual N)
- stem length or crop height (see section 5.2.1)
- ear size (see section 5.2.1)

Results from the MT94 experiment (Table 5.21) showed that full rate PGR (5C+T) shortened height by just over 10 cm (13%) and centre of gravity by just over 5 cm (11%), compared to the NIL 'control' treatment. PGR treatments had significantly shorter internodes 3, 4 and 5 than the NIL and G5 treatments, but full PGR (5C+T) treatments were not significantly shorter than with 5C alone. The length of internodes 1 and 2 was not significantly affected by lodging control treatments. Centre of gravity and internode lengths were not significantly affected by sowing date except internode 2 length, which was significantly longer with the early sown crop.

Table 5.21 The effect of lodging control on centre of gravity and upper internode lengths at GS 72 in the MT94 experiment.

Treatment	Centre gravity (m)	Internode 5 length (mm)	Internode 4 length (mm)	Internode 3 length (mm)
NIL	0.495	277	187	147
5C	0.442	243	153	116
5C+T	0.442	239	147	111
G5	0.513	298	199	151
SEM	0.0089	7.9	4.3	4.3
p-value	<0.001	<0.001	<0.001	<0.001
CV%	4.6	7.3	6.1	8.0
LSD (12df)	0.0275	24.3	13.1	13.2

Table 5.22 The effect of lodging control on centre of gravity and upper internode lengths at GS 72 in the ST94 experiment.

Treatment	Centre gravity (m)	Internode 5 length (mm)	Internode 3 length (mm)
NIL	0.496	222	114
5C	0.471	226	108
5C+T	0.462	197	99
G5	0.440	231	113
SEM	0.0053	6.5	3.5
p-value	<0.001	<0.05	<0.05
CV%	2.8	7.3	7.8
LSD (12df)	0.0163	20.0	10.7

The NIL 'control' treatment in the ST94 experiment (Table 5.22) had a significantly higher centre of gravity (by 3-5 cm) than the 5C, 5C+T and G5 treatments at GS 72.

The 5C and 5C+T PGR treatments reduced internode 3 length by 6 mm (5%) and 15 mm (13%) respectively, compared to the NIL 'control'. G5 internode 3 and 5 lengths were similar to the NIL 'control' treatment. There was an interaction between sowing date and lodging control ($p<0.05$) at GS 72 in the ST94 experiment, whereby internode 4 length was significantly shorter for the late sown G5 treatment; this was also evident for total stem length (Table 5.15) and centre of gravity (Table 5.22). Centre of gravity and internode lengths were not significantly affected by sowing date at GS 72. Internode 1 length was not significantly affected by lodging control treatment, but internode 2 lengths for 5C+T and G5 were significantly shorter than for the NIL 'control'.

Table 5.23 The effect of sowing date, seed rate, residual nitrogen and lodging control on internode 1 length at GS 87 in the MT95 experiment.

	TOS 1	TOS 2		HSR	LSR
Internode 1 length (mm)	36.8	43.7		38.1	42.3
	330-N	30-N	NIL	5C	5C+T
Internode 1 length (mm)	41.3	39.2	44.5	37.4	38.9
(df)	**SEM**	**p-value**		**CV%**	**LSD**
Sowing date (2)	1.01	<0.05		4.4	6.17
Seed rate (4)	0.75	<0.05		4.6	2.96
Residual nitrogen (40)	0.79	0.066		11.8	-
Lodging control (40)	0.97	<0.001		11.8	0.89

Table 5.23 shows that significant variation in the length of internode 1 (from 2-7 mm) occurred as a result of sowing date, seed rate and lodging control treatments in MT95. As expected, PGR application decreased length (by approximately 7 mm compared to the NIL 'control'), but early sowing and high seed rate which were expected to increase length did not. Internode 1 length was significantly longer in the late sown crop (by 7 mm) and in the low seed rate crop (by 4 mm) at GS 87. High residual nitrogen levels increased internode 1 length by 2 mm, but the difference was not significant. An interaction between sowing date and lodging control for internode 2 length ($p<0.01$) also unexpectedly showed that internode length was greater for the late sown crop (by 8 mm on average) for all three lodging control treatments. Application of PGR reduced internode 2 length by 10-20 mm for both

sowing dates, as expected. Basal internode length was not significantly affected by any agronomic treatments imposed.

In the MT95 experiment (Table 5.24), the 5C PGR treatment had a significantly shorter internode 3 (by 22 mm) than the NIL 'control' treatment, but for the late sown crop only. Internode 4 length was significantly reduced by both 5C and 5C+T PGR treatments, for both sowing dates. Applying full PGR (5C+T) reduced the length of internode 4 by 38 mm on average. Both PGR treatments significantly reduced peduncle length, by up to 58 mm (19%) with 5C+T.

Table 5.24 The effect of sowing date and lodging control on upper internode lengths at GS 87 in the MT95 experiment.

	TOS 1			TOS 2		
	NIL	5C	5C+T	NIL	5C	5C+T
Internode 3 length (mm)	114	114	112	140	118	113
Internode 4 length (mm)	191	179	166	204	179	151
	NIL	5C	5C+T			
Peduncle length (mm)	312	292	254			
(40df)	**SEM**	**p-value**		**CV%**	**LSD**	
Internode 3 length	1.6	<0.001		4.8	5.3	
Internode 4 length	3.4	<0.001		6.6	8.9	
Peduncle length	2.3	<0.001		4.9	8.3	

Table 5.25 The effect of sowing date, seed rate and residual nitrogen on centre of gravity at GS 69 in the MT95 experiment.

Residual nitrogen treatment	TOS 1		TOS 2	
	HSR	LSR	HSR	LSR
330-N	0.432	0.407	0.408	0.415
30-N	0.403	0.406	0.398	0.404
(56df)	**SEM**	**p-value**	**CV%**	**LSD**
Centre gravity	0.0044	<0.05	3.7	0.0149

In the MT95 experiment, an interaction between sowing date, seed rate and residual nitrogen occurred for centre of gravity at GS 69 (Table 5.25). The early sown, high seed rate, high residual nitrogen crop had a significantly higher centre of gravity (by 3 cm) than the late sown treatments, low seed rates and low residual Ns. Early sown crops in high nitrogen situations were expected to produce taller, heavier canopies.

Lodging control was significant as a main effect. The application of 5C decreased centre of gravity, which was further decreased by 5C+T. The G5 treatment had a lower centre of gravity than the NIL 'control', similar to the reduction produced by 5C PGR.

Results from the VT95 experiment (Table 5.26), showed that the centre of gravity was not significantly different between varieties, apart from Little Joss, for which it was between 27-30 cm higher. Centre of gravity measured on the whole plant (all shoots) was consistently lower than for the main stem only, but the difference was small (4-26 mm).

Table 5.26 The effect of variety on height at the centre of gravity at GS 65 in the VT95 experiment.

Variety	Centre gravity (m) MS only	Centre gravity (m) plant
Hereward	0.389	0.384
Riband	0.389	0.384
Mercia	0.370	0.364
Cadenza	0.387	0.391
Beaver	0.380	0.374
Little Joss	0.666	0.640
SEM	0.0104	0.0121
p-value	<0.001	<0.001
CV%	4.6	5.4
LSD (42df)	0.0298	0.0344

Summary of centre of gravity

For the variety Mercia, the extent of variation in the height at the centre of gravity in July was from 5-6 cm for MT94 and ST94. The variation was due only to lodging control treatments in the 1993-94 season, with the 5C+T PGR decreasing the centre of gravity most compared to NIL 'control' and G5 treatments. Variation in centre of gravity during July was greater in MT95, by up to 11 cm, and was due to differences in a sowing date, seed rate and residual N interaction. Varietal variation in centre of gravity was small between modern cultivars (about 2 cm). Large variation only existed in the older variety, Little Joss, which had a centre of gravity nearly 30 cm higher than modern cultivars.

5.2.3 *Shoot number*

Shoot number per plant was expected to be influenced by seed rate, residual nitrogen, sowing date and variety. Shoot number per plant was not significantly affected by the sowing date or lodging control treatments in the MT94 or ST94 experiments at GS 72.

In the MT95 experiment (Table 5.27), the NIL 'control' had a significantly greater shoot number per plant than all other lodging control treatments, with G5 being the lowest. The low seed rate crop had over 1 shoot per plant more than the high seed rate, and high residual nitrogen significantly increased shoot number per plant. Shoot number at GS 69 was not significantly affected by sowing date.

Table 5.27 The effect of seed rate, residual nitrogen and lodging control on plant shoot number at GS 69 in the MT95 experiment.

Lodging control	Shoot number /plant	Seed rate	Shoot number /plant	Residual nitrogen	Shoot number /plant
NIL	2.9	HSR	2.0	330-N	2.7
5C	2.6	LSR	3.2	30-N	2.5
5C+T	2.6				
G5	2.5				
(df)		**SEM**	**p-value**	**CV%**	**LSD**
Lodging control (56)		0.12	<0.01	16.4	0.25
Seed rate (4)		0.06	<0.001	5.6	0.24
Residual nitrogen (56)		0.12	<0.05	16.4	0.18

Beaver had significantly more shoots per plant than Little Joss, Riband or Cadenza in the VT95 experiment (Table 5.28).

Table 5.28 The effect of variety on plant shoot number at GS 65 in the VT95 experiment.

Variety	Hereward	Riband	Mercia
Shoot number/plant	1.8	1.5	1.8
Variety	Cadenza	Beaver	Little Joss
Shoot number/plant	1.5	2.3	1.6

(42df)	**SEM**	**p-value**	**CV%**	**LSD**
Variety	0.19	<0.001	17.2	0.54

Summary of shoot number per plant

For the variety Mercia, the extent of variation in plant shoot number was just over one shoot per plant for MT95. Most variation was controlled by seed rate, the low seed rate producing more than one extra shoot per plant. Variation to a lesser extent was also caused by lodging control treatments, all of which reduced shoot number per plant compared to the NIL 'lodging control', and high residual nitrogen which increased plant shoot number. The extent of variation between the subset of six varieties in VT95 was small except for Beaver, which had between 0.5-0.8 more shoots per plant than the other varieties.

5.3 Stem base characteristics

5.3.1 *Stem base bending moment*

The following crop characteristics are expected to influence the failure moment (strength) of the stem base, and their possible determinants are shown in brackets:

- stem bending/failure moment (seed rate, residual N, PGR, stem base disease)
- stem diameter (seed rate, residual N, PGR)
- stem wall width (PGR, variety, seed rate, residual N)

No significant treatment effects were obtained for stem base characteristics in the MT94 or ST94 experiments (stem bending moment and stem wall width were not calculated in these experiments. In both experiments, the diameters of all lower internodes were measured at GS 72, and despite agronomic control using PGRs, and sowing date differences, the diameter was not significantly altered despite adequate levels of precision (CV = 3.8-5.7%), which was not as expected.

The following results refer to two treatments which showed a large contrast between physical structure of plants, due to differing agronomy imposed on them. Only two treatments were analysed due to the time constraints involved in these more detailed measurements. Statistics presented for these two treatments are derived from analysis of the two treatments only (based on six plots).

Table 5.29 The effect of different agronomic risk treatments on stem base characteristics at GS 59 in the MT95 experiment.

Treatment	Stem base plant diameter (mm)	Internode 1 stem failure moment (Nm)	Internode 2 stem failure moment (Nm)
1HN3	3.5	0.132	0.098
2LO3	12.0	0.276	0.237
SEM	0.80	0.0205	0.0118
p-value	<0.05	<0.05	<0.01
CV%	18.0	17.4	12.2
LSD (2df)	4.89	0.1240	0.0720

NB: Stem base diameter measured the diameter of all shoots at the plant base.

In the MT95 experiment (Table 5.29), the 1HN3 treatment (early sown, high seed rate, high residual nitrogen and full PGR) was expected to have a greater lodging risk than the 2LO3 treatment (late sown, low seed rate, low residual nitrogen and full PGR). The high risk 1HN3 treatment had a significantly narrower stem base (by c.8mm) than the low risk 2LO3 treatment at GS 59. 1HN3 also had significantly lower (weaker) failure moments than 2LO3 for internodes 1 and 2, by 52% and 59% respectively. The main cause of these large differences is probably due to seed rate and therefore plant density, although these differences were not apparent for stem diameter of the basal, 1 and 2 internodes at GS 59.

Table 5.30 The effect of different agronomic risk treatments on stem base characteristics at GS 72 in the MT95 experiment.

Treatment	Basal internode stem failure moment (Nm)	Basal internode diameter (mm)
1HN3	0.087	2.6
2LO3	0.119	3.1
SEM	0.0013	-
p-value	<0.05	<0.05
CV%	2.2	1.6
LSD (2df)	0.0078	0.16

At GS 72 in the MT95 experiment (Table 5.30), treatment 1HN3 also had significantly weaker failure moments than 2LO3 for all the lower internodes, but only the basal internode showed a significant difference: the diameters of internodes 1 and

2 were not significantly affected by treatment (as at GS 59), but basal diameter was larger for 2LO3 at GS 72. Stem wall width was not significantly different between treatments at GS 72, although it was consistently greater for 2LO3 compared to 1HN3.

Results from the MT95 experiment (Table 5.31), showed that severe disease infection significantly reduced (weakened) the stem failure moment for internode 2. The stem failure moment (compared to disease-free stems) was reduced by 0.032 Nm (44%) for severe fusarium infection, and by 0.025 Nm (32%) for severe sharp eyespot infection.

Table 5.31 The effect of stem base disease severity on stem failure moment at GS 87 in the MT95 experiment.

Disease severity	Fusarium: internode 2 stem failure moment (Nm)	Sharp eyespot: internode 2 stem failure moment (Nm)
Clean	0.072	0.072
Slight	0.070	0.080
Moderate	0.066	0.062
Severe	0.040	0.049
SEM	0.0053	-
p-value	<0.01	<0.01
CV%	20.9	7.6
LSD (12df)	0.0163	0.0131

In the MT95 experiment (Table 5.32), treatment 1HN1 represents a high lodging risk with no PGRs applied, whereas treatment 1HN3 is the same but with a full PGR application of 5C+T. By averaging clean, slight, moderate and severe categories of fusarium infection on internode 2, the 1HN3 treatment had a significantly lower failure moment (0.058 Nm) than the 1HN1 treatment (0.065 Nm). This represented an 11% decrease in stem bending strength with the application of 5C+T PGRs, which was not as expected. Even in absence of disease infection (clean stems only), the PGR treatment still had a 7% weaker stem than the non-PGR treatment. For sharp eyespot infection on internode 2, PGR application did not increase stem failure moment significantly.

Table 5.32 The effect of PGR application on internode 2 stem failure moment at GS 87 in the MT95 experiment.

Disease severity (fusarium)	1HN1 stem failure moment (Nm)	1HN3 stem failure moment (Nm)
Clean	0.074	0.069
Slight	0.075	0.065
Moderate	0.072	0.059
Severe	0.040	0.040
SEM	-	-
p-value	<0.05	<0.05
CV%	1.9	1.9
LSD (12df)	0.004	0.004

Table 5.33 The effect of seed rate and residual nitrogen on diameter of basal internodes at GS 87 in the MT95 experiment.

	HSR	LSR	330-N	30-N
Internode 1 diameter (mm)	3.20	3.39	-	-
Internode 2 diameter (mm)	3.52	3.85	3.58	3.78
(df)	**SEM**	**p-value**	**CV%**	**LSD**
Internode 1.seed rate (4)	0.041	<0.05	3.0	0.159
Internode 2.seed rate (4)	0.075	<0.05	5.0	0.293
Internode 2.residual N (40)	0.068	<0.05	11.1	0.197

Agronomic control treatments did not significantly affect the diameter of basal internodes in the MT95 experiment at GS 87 (Table 5.33). However, diameters for internodes 1 and 2 were significantly greater with the low seed rate by 0.2 mm and 0.3 mm, and the internode 2 diameter was also significantly greater (by 0.2 mm) with the low residual nitrogen treatment.

Basal internode failure moments in the VT95 experiment (Table 5.34) were greatest (strongest) in Buster, Hereward and Riband, varieties which possess high standing power (NIAB, 1995). Buster (with the highest standing power rating of 9) had a significantly greater failure moment (0.02-0.09 Nm) than all other varieties except Hereward. Differences between the varieties were less for internodes 1 and 2, with Mercia and Riband having a significantly stronger internode 1 than the other varieties.

Table 5.34 The effect of variety on stem failure moment at GS 65 in the VT95 experiment.

Variety	Basal internode failure moment (Nm)	Internode 1 failure moment (Nm)	Internode 2 failure moment (Nm)
Buster	0.203	0.198	0.163
Riband	0.154	0.235	0.193
Hereward	0.178	0.205	0.121
Mercia	0.136	0.237	0.212
Cadenza	0.131	0.198	0.169
Beaver	0.129	0.187	0.138
Little Joss	0.111	0.175	0.146
SEM	0.012	0.011	0.012
p-value	<0.01	<0.001	<0.001
CV%	14.4	9.3	13.2
lLSD (14df)	0.036	0.032	0.036

Table 5.35 The effect of variety on weight per unit length of the lower internodes at GS65 in the VT95 experiment.

Variety	Basal internode weight (g/cm)	Internode 1 weight (g/cm)	Internode 2 weight (g/cm)
Buster	-	-	-
Riband	0.157	0.142	0.151
Hereward	0.107	0.118	0.123
Mercia	0.122	0.111	0.127
Cadenza	-	-	-
Beaver	0.097	0.109	0.119
Little Joss	0.094	0.084	0.081
SEM	0.001	0.001	0.008
p-value	<0.05	<0.01	<0.001
CV%	18.7	7.8	7.2
lLSD (10df)	0.004	0.002	0.024

In the VT95 experiment (Table 5.35), the varieties Beaver and Little Joss had the least weight per length for all the lower internodes. Riband had the greatest weight per length for each internode. The extent of variation due to variety was 0.06-0.07 g/cm for the lower internodes.

Table 5.36 The effect of variety on the stem wall width and diameter of the lower internodes (IN) at GS 65 in the VT95 experiment.

Variety	Basal stem wall width (mm)	IN1 stem wall width (mm)	IN2 stem wall width (mm)	Basal diameter (mm)	IN1 diameter (mm)	IN2 diameter (mm)
Buster	-	-	-	3.27	3.70	4.08
Riband	0.783	0.790	0.877	3.43	4.32	4.85
Hereward	0.823	0.920	0.940	3.22	3.77	4.29
Mercia	0.587	0.683	0.673	3.12	3.66	4.28
Cadenza	-	-	-	3.16	3.58	4.12
Beaver	0.667	0.705	0.862	2.93	3.37	4.00
Little Joss	0.563	0.563	0.503	2.97	3.49	4.05
SEM	0.0366	0.0421	0.0376	0.101	0.082	0.102
p-value	<0.01	<0.01	<0.001	<0.05	<0.001	<0.001
CV%	9.3	10.0	8.3	5.6	3.9	4.2
LSD	0.1152	0.1326	0.1183	0.306	0.247	0.308
(df)	(10)	(10)	(10)	(14)	(14)	(14)

In the VT95 experiment, Hereward had a significantly thicker stem wall width for basal, 1st and 2nd internodes, than all other varieties, except for internode 2 of Riband (Table 5.36). Little Joss and Mercia had stem wall widths 0.25 and 0.45 mm thinner than Hereward. Beaver had the smallest stem diameter for basal, 1st and 2nd internodes, which may account for Beaver being prone to stem lodging (NIAB, 1995; ADAS, unpublished). The high standing power varieties Buster, Riband and Hereward had the largest diameters for basal internodes and for internode 1 and internode 2.

Summary of stem base bending moment

The extent of variation in the stem base failure moment for the variety Mercia in the MT95 was approximately 0.09-0.28 Nm, controlled mainly by seed rate. Severe stem base disease infection further extended the variation by reducing stem failure moment to 0.04 Nm. PGR application did not increase stem failure moment as expected. Variation in stem failure moment occurred between varieties, with Buster (high standing power) at 0.20 Nm, Beaver (low standing power) at 0.13 Nm and Little Joss (old variety) at 0.11 Nm. For the variety Mercia, variation in diameter of the lower internodes for different treatments was small: about 0.6 mm for basal internodes, 0.5-0.8 mm for internode 1 and 0.7-1.0 mm for internode 2. Diameter was controlled mainly by seed rate and not by PGR application, as expected. Variation in stem diameter of up to 1 mm occurred between varieties, with Riband having the greatest stem diameter and Beaver the smallest, which agreed with NIAB varietal standing powers (NIAB, 1995). In the MT95 experiment, agronomic treatments did not significantly alter stem wall width in Mercia. However, significant variation occurred between varieties in the VT95 trial. The varieties Hereward and Riband with high standing power (NIAB, 1995) had thicker stem walls (by 0.2 mm on average) than the varieties Mercia, Beaver and Little Joss, with low NIAB standing power ratings. It is important to recognise that the stem base characteristics described are not the whole explanation of standing power, with the canopy and root structure of the plant, and the soil characteristics, of equal if not greater importance (Griffin & Berry, unpublished).

5.4 Root characteristics

5.4.1 *Crown root anchorage*

The following crop characteristics are expected to influence the strength and anchorage of the structural crown root system; their possible determinants are shown in brackets:

- root bending or failure moment (variety, sowing date, seed rate)
- root cone diameter (variety, sowing date, seed rate)
- crown depth ('Baytan' seed treatment)

Table 5.37 The effect of the seed treatment 'Baytan' on the root cone diameter and crown depth at GS 31.

Treatment	Root cone diameter 1 (mm)	Root crown depth (mm)
Baytan	24.1	24.9
Untreated	19.9	18.6
SEM	0.61	1.36
p-value	<0.01	<0.05
CV%	6.8	15.4
LSD (5df)	2.22	4.96

Source of data: Take-all experiment, ADAS Rosemaund 1995.

The results in Table 5.37 were obtained from a separate experimental trial. Sampling and measurement of plants were performed identically to the methods described for the main experiments (i.e. ten plants per replicate plot were sampled). Baytan treated plants had significantly larger root cone diameters (over 4 mm larger) and deeper crowns (6.5 mm deeper) than untreated plants; increases of 17% and 25% respectively from use of 'Baytan'. These results suggest that Baytan may reduce lodging, not only by causing plants to set deeper crowns which improves root anchorage, but also by encouraging earlier crown root growth, resulting in larger root cone diameters.

In both the MT94 and ST94 experiments, no significant effects were detected for the root characteristics measured (crown root number, angle of crown root spread, crown width and rigid crown root length). Agronomic comparisons were restricted to sowing date and lodging control. These particular controls seemed ineffective in these experiments, but also the lack of significant differences could be due to some of the measurement methods. The measurements of crown root angle and rigid root length were difficult to make with confidence, which was further evident from the CVs of these measurements which were fairly high. The CV ranged from 7.5-15.1% for crown root angle and 9.6-18.8% for rigid crown root length, in both experiments. For these reasons, the more robust measurement of root cone diameter was introduced in the MT95 experiment.

Table 5.38 The effect of sowing date on below-ground biomass at GS 72 and GS 87 in the MT94 experiment.

Treatment	Below-ground dry weight (t/ha)	Below-ground fresh weight	Below-ground dry weight (t/ha)	Below-ground fresh weight
TOS 1	3.44 (GS 72)	6.87 (GS 72)	1.31 (GS 87)	4.00 (GS 87)
TOS 2	1.78	3.54	1.10	2.19
SEM	0.132	0.327	0.017	0.095
p-value	<0.01	<0.05	<0.01	<0.01
CV%	8.7	10.9	2.5	5.3
LSD (2df)	0.800	1.988	0.105	0.577

Both the fresh weight and dry weight of below-ground plant material in the MT94 experiment (Table 5.38) was significantly greater for the early sown crop than for the late sown crop at GS 72 and GS 87. When fresh weight at GS 72 was converted from tonnes/hectare into grams/plant, the early sown crop had 3.5 g/plant of root and below-ground stem material compared to 1.8 g/plant in than the late sown crop (nearly twice as much). This difference was similar at GS 87. Lodging control treatments did not significantly affect below-ground fresh or dry weight.

The 1HN3 treatment in the MT95 experiment at GS 59 produced a significantly smaller maximum ($p<0.05$) and minimum ($p<0.01$) root cone diameter (c.10 mm less on average) than the 2LO3 treatment. The 2LO3 treatment also produced over twice as many crown roots ($p<0.05$) than 1HN3 at GS 59. At GS 72, this treatment also had a significantly ($p<0.05$) wider crown (by 3.5 mm) than 1HN3, and double the rigid root length ($p<0.05$). However, the angle of root spread was not significantly different (as found in MT94 and ST94) between the above treatments suggesting that angle of spread is an imprecise measurement, also evident from its high CV (13.2-23.8%). Crown depth, which may influence anchorage, was not affected by agronomic treatments at GS 59 or GS 72.

Table 5.39 The effect of seed rate and sowing date on root cone diameter at GS 69 in the MT95 experiment.

Treatment	Root cone diameter 1 (mm)		Root cone diameter 2 (mm)	
	TOS 1	TOS 2	TOS 1	TOS 2
HSR	29.66	30.82	20.38	20.74
LSR	33.96	40.31	24.13	29.92
(4df)	**SEM**	**p-value**	**CV%**	**LSD**
Root cone diameter 1	0.583	<0.01	3.0	3.380
Root cone diameter 2	0.438	<0.01	3.2	3.600

In the MT95 experiment (Table 5.39), for both root cone diameter 1 (maximum root spread) and cone diameter 2 (minimum root spread), the early sown, high seed rate crop was not significantly different to the late sown, high seed rate crop at GS 69. Root cone diameter of the low seed rate was significantly larger (by 4-10 mm) than the high seed rate for both sowing dates. By averaging root cone diameters 1 and 2, the early and late sown, low seed rate crops had 15% and 28% larger average root cone diameters than the equivalent high seed rate crops. Residual nitrogen and lodging control treatments did not significantly affect root cone diameter at GS 69.

Table 5.40 The effect of seed rate on crown root number and root anchorage strength in July for the MT95 experiment.

Treatment	Crown root number (GS 69)	Root resistance (Nm) 18-July	Root resistance (Nm) 28-July
HSR	8.30	0.050	0.039
LSR	11.56	0.133	0.113
SEM	0.250	0.0102	0.0056
p-value	<0.001	<0.001	<0.001
CV%	6.2	33.2	21.9
LSD	0.98	0.032	0.018
(df)	(4)	(10)	(10)

In the MT95 experiment (Table 5.40), the low seed rate crop had 28% more crown roots (3 per plant) than the high seed rate crop at GS 69. The other agronomic treatments did not significantly influence crown root number at GS 69. Seed rate was the controlling factor influencing the number of structural roots. Root resistance of the low seed rate crop was significantly greater (by 62%-66%) than the high seed rate crop in mid to late July, which probably relates to the greater number of structural roots and larger root cone diameter of the low seed rate crop.

Table 5.41 The effect of variety on various root characteristics at GS 65 in the VT95 experiment.

Variety	Root crown depth (mm)	Crown root number	Root cone diameter 1 (mm)	Root cone diameter 2 (mm)
Buster	25.4	9.9	36.0	25.9
Riband	17.2	11.9	39.6	31.3
Hereward	22.9	12.5	40.5	28.8
Cadenza	27.7	8.6	27.9	19.0
Mercia	15.1	10.1	36.9	24.5
Beaver	15.3	13.5	45.3	32.4
Little Joss	19.7	9.3	32.4	23.0
SEM	1.77	0.80	2.13	1.75
p-value	<0.001	<0.001	<0.001	<0.001
CV%	15.6	13.0	10.1	11.7
LSD	5.06	2.30	6.09	4.99
(42df)				

Previous experience has shown that lower seed rates often produce a stronger rooting structure, leading to better plant anchorage due to less inter-plant competition (Easson *et al.*, 1993; 1995). Crown depth varied by up to 12 mm between varieties in the VT95 experiment (Table 5.41), Cadenza and Buster having the deepest crowns (suggesting good anchorage) and Mercia and Beaver having the shallowest crowns (suggesting poor anchorage). Crown root number varied by up to five per plant between varieties. Beaver (low standing power rating) had the largest root cone diameter and the greatest rigid root length of all the varieties.

Summary of crown root anchorage

The extent of variation in root anchorage characteristics was very small in the MT94 (cv. Mercia) and ST94 (cv. Riband) experiments, with sowing date and lodging control treatments proving ineffective in influencing root structure. However, in the 1994-95 season, much more variation in root structure occurred for the variety Mercia. Root cone diameter varied by 20-40 mm, crown root number by 7-15 per plant and root resistance by 0.04-0.13 Nm. Seed rate was the dominant agronomic factor which controlled this variation. PGRs and residual N did not influence root structure. Crown depth, apart from being influenced directly by drilling depth, was strongly influenced by 'Baytan' seed treatment, which also improved root cone diameter. In the VT95 trial, considerable variation in root structure occurred between varieties. Crown depth varied by as much as 12 mm, root number by up to 5 per plant and root cone diameter by up to 15 mm. Results clearly showed that rooting structure differences between varieties could not be explained by the NIAB standing power ratings of the particular varieties tested.

5.5 Summary of the major factors influencing plant structure

Table 5.42 below, indicates the agronomic factor(s) which most influenced the various plant characters described in the previous sections 5.1, 5.2, 5.3 & 5.4. Sowing date did affect canopy architecture and was influential only when the sowing date was very early (e.g. MT96 experiment), which produced a considerable larger canopy size. The canopy height was most influenced by lodging control. Both stem structure and root structure were most influenced by seed rate, though varietal differences also occurred. Refer to 'common perceptions' described in section 1.2.

Table 5.42 Summary of the most influential factors affecting the plant characters used in the model.

Plant character	Sowing date	Seed rate	Residual nitrogen	Lodging control	Variety	Others
Natural frequency	-	-	-	*yes*	-	*rainfall*
Centre gravity	-	-	-	*yes*	-	-
Shoot number	-	*yes*	-	-	*yes*	-
Stem failure moment	-	*yes*	-	-	*yes*	*disease*
Stem radius	-	*yes*	-	-	-	-
Stem wall width	-	-	-	-	*yes*	-
Root failure moment	-	*yes*	-	-	*yes*	*wet soil*
Root cone diameter	-	*yes*	-	-	-	-
Rooting depth	-	*yes*	-	-	-	*drilling depth*

5.6 Final crop lodging scores

Very little lodging occurred in the MT94 experiment (Table 5.43), except for a few small patches in both early and later sowing dates, high seed rate, high residual nitrogen and NIL 'control'. The lodging which occurred just before harvest was caused by root failure after rain showers at the beginning of August. No lodging occurred in ST94 probably because, although it was earlier sown and higher density, the soil strength in the top 2-5 cm of soil was much greater than in MT94. Also, the variety Riband in ST94 was stiffer strawed and better anchored (with more crown roots and a larger structural root cone) than Mercia in the MT94. With even drier weather in the summer of 1995, no widespread lodging occurred in the MT95 experiment. The lodging which occurred was mainly confined to higher risk treatments (Table 5.44). Nearly 75% of the early sown, high seed rate, high residual nitrogen and NIL 'control' treatment leaned or lodged from mid to late July. The next most affected treatments were both early sown and high seed rate followed by either low residual nitrogen with NIL 'control' or high residual nitrogen with G5.

Table 5.43 Final lodging scores for the MT94 experiment.

Treatment	% upright (0°-4°)	% leaning (5°-44°)	% lodged (45°-89°)	% lodged flat (90°)
2HN1	87	6	7	-
1HN1	90	5	5	-
1HN2	98	2	-	-
1HO1	99	1	-	-
2HO1	99	1	-	-

NB: All lodging was caused by root failure and lodging was recorded in no other treatments except those above. Degree values (°) represent angle from the vertical.

About a third of these treatments leaned, but only 7-10% lodged. Small amounts of leaning occurred in some other treatments (mainly early sown and high seed rate). All the lodging in the MT95 experiment was caused by stem failure, see Plate 5.1 (Appendix 1), and took place between mid-July and early August. Stems of lodged plants buckled at either the basal internode or internode 1, see Plate 5.2 (Appendix 1), and a large proportion of stem failure was associated with severe fusarium and sharp eyespot infection of the stem base. Of the six varieties intensively monitored in the VT95 trial, only Little Joss lodged due to failure of the lower internodes, giving a total of 24% of the plots leaning and 18% lodging at harvest.

Table 5.44 Final lodging scores for the MT95 experiment.

Treatment	% upright (0°-4°)	% leaning (5°-44°)	% lodged (45°-89°)	% lodged flat (90°)
1HN1	28	37	12	23
1HO1	64	26	5	5
1HN4	60	33	7	-
1HO3	93	-	7	-
1HO2	92	6	-	2
1HN2	93	5	2	-
1HO4	92	8	-	-
1HN3	95	5	-	-
1LO1	97	3	-	-
1LN4	98	2	-	-
1LN1	98	2	-	-

NB: 1HN1 treatment initially lodged in one plot due to animal damage (10%). Lodging was recorded in no other treatments except those above.

In the 1996 season, much more severe, widespread lodging took place than in the previous two seasons. Lodging was caused by root failure in all plots, see Plate 4.3 (Appendix 1), and was associated with periods of rainfall which caused wetting and weakening of the surface layer of soil, see Plate 4.4 (Appendix 1). A total of four main lodging events occurred between mid-June and harvest, all of which were during or shortly after rainfall. The first lodging event occurred on 12 June between 0600-1800 hours. Within this 12 h period, the wind speeds averaged just over 2 m/s (maximum speed = 7.72 m/s) and a total of 6.6 mm rainfall was recorded. The second lodging period occurred between 18-24 July, the third between 29-31 July and the final lodging event occurred pre-harvest between 9-11 August. Figs 5.9-5.16 show both the severity and duration of lodging in all treatments which lodged before 11 August, and are plotted in the order in which treatments lodged. On 12 June (Fig. 5.9) substantial lodging occurred in two treatments; 1HN1 and 1LN1 (see Treatment Codes). As expected, the early sown, high seed rate, high residual N, NIL 'control' crop lodged first and most severely, and was effectively all lodged by harvest. The equivalent low seed rate treatment (1LN1) also lodged quite severely from 12 June; the positive effects expected from the low seed rate were seemingly unable to compensate for the negative effects expected from early sowing, high residual N and no PGR.

The treatments which first lodged between mid-June to mid-July (Figs 5.9-5.11) were all early sown (as expected); 6 out of 10 were high seed rate, 7 out of 10 had high residual N and 6 out of 10 had no PGR applied. Treatments which first lodged between end-July to early-August (Figs 5.12-5.15), were generally less severely affected than previous treatments. Some late sown treatments lodged (such as 2HN1 and 2HO1 which were approximately 50% lodged by harvest) as well as some full 5C+T PGR treatments. Generally, 5C+T treatments prevented severe lodging with the exception of 1HN3 which was c.40% lodged by harvest. The treatments which first lodged late in the season (pre-harvest) all had approximately 10% or less lodging by harvest (Fig. 5.16). A further seven treatments (not shown in the figures) had 3% or less lodging by harvest, leaving only two treatments (2LO3 and 2LN4) which had no lodging by harvest. The 2LO3 treatment (late sown, low seed rate, low residual N and full 5C+T PGR) was the crop with least lodging, as expected. For the 2LN4 treatment, it is likely that the canopy management G5 treatment compensated well for the high residual N to prevent lodging.

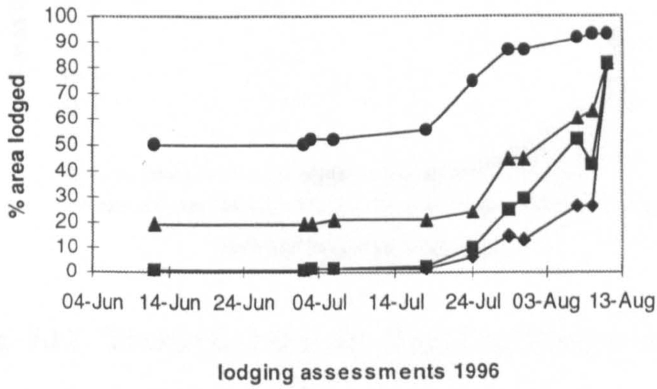

Fig. 5.9. Treatments which first lodged on 12 June in the MT96 experiment.

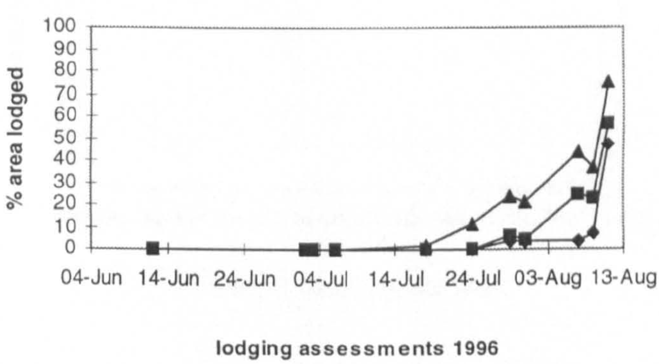

Fig. 5.10. Treatments which first lodged on 6 July or 18 July in the MT96 experiment.

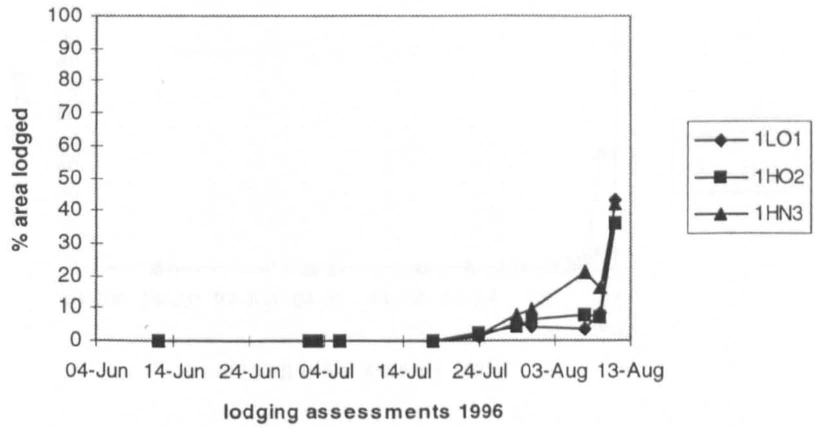

Fig. 5.11. Treatments which first lodged on 24 July in the MT96 experiment.

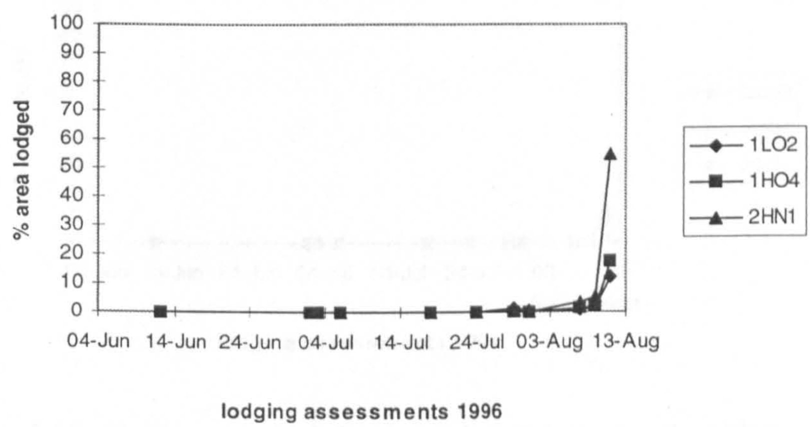

Fig. 5.12. Treatments which first lodged on 29 July in the MT96 experiment.

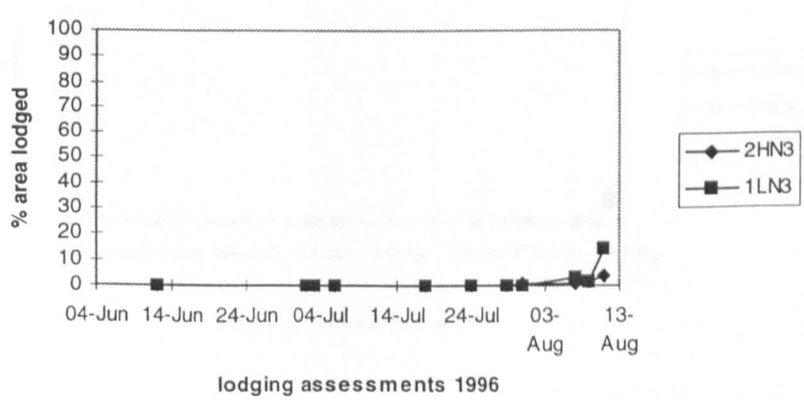

Fig. 5.13. Treatments which first lodged on 31 July in the MT96 experiment.

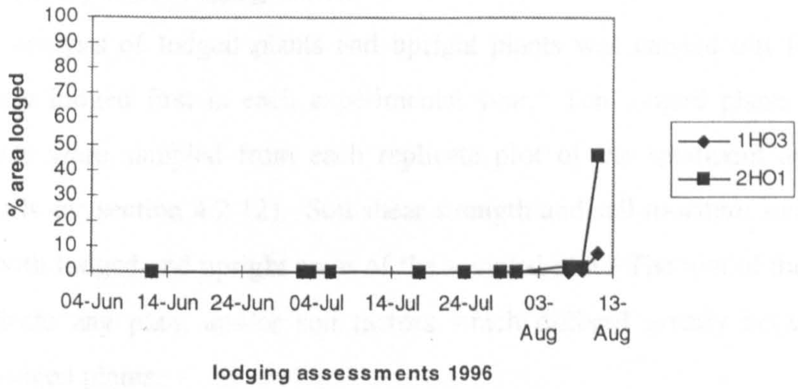

Fig. 5.14. Treatments which first lodged on 7 August in the MT96 experiment.

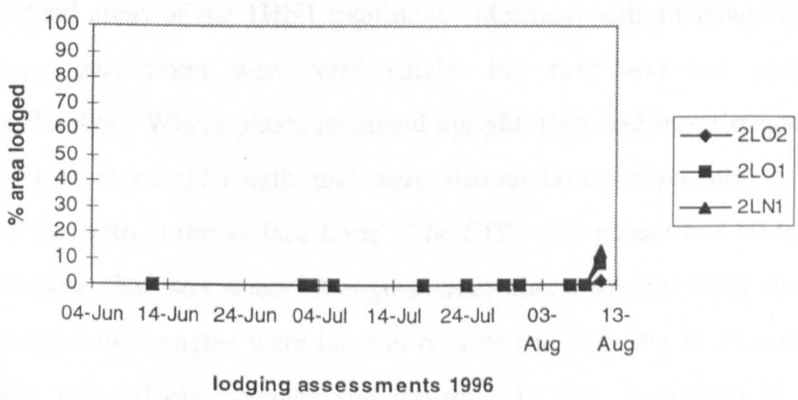

Fig. 5.15. Treatments which first lodged on 9 August in the MT96 experiment.

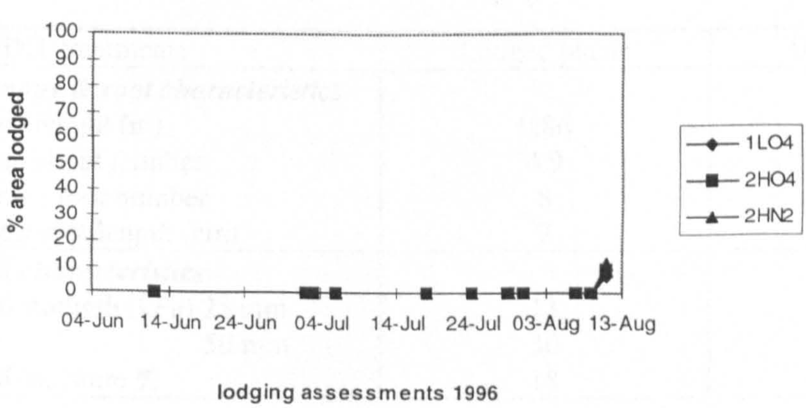

Fig. 5.16. Treatments which first lodged on 11 August in the MT96 experiment.

5.7 Analysis of lodging events

An analysis of lodged plants and upright plants was carried out for the treatment which lodged first in each experimental year. Ten lodged plants and ten upright plants were sampled from each replicate plot of the treatment and analysed (for details see section 4.2.12). Soil shear strength and soil moisture were also measured in both lodged and upright areas of the sampled plot. The aim of the analysis was to indicate any plant and/or soil factors which differed greatly between lodged and unlodged plants.

In the MT94 experiment (Table 5.45), small patches of root lodging occurred in a few plots, mainly in the 1HN1 treatment. Plants were analysed from lodged and unlodged areas of the 1HN1 treatment. Measurements indicated that above-ground canopy parameters were very similar but root and soil parameters differed considerably. Where plants remained upright, they had more structural crown roots with a greater rigid length, and were also anchored in patches of soil with greater shear strength in the surface layer. The ST94 experiment had no lodging and it was noticeable that soil shear strengths were much greater than at the MT94 site. Average soil strengths were large at 65 kPa and 100 kPa at 25 mm and 50 mm soil depths respectively (average soil moisture 12.3%), compared to the much lower values of soil strength in Table 6.5.

Table 5.45 An analysis of lodged and upright plants in the MT94 experiment.

(1HN1 treatment)	Lodged plants	Upright plants
Canopy & root characteristics		
Plant height (m)	0.86	0.86
Plant shoot number	4.9	5.2
Crown root number	8	11
Rigid root length (cm)	7	11
Soil characteristics		
Soil strength (kPa) 25 mm	18	26
50 mm	30	42
Soil moisture %	18	16

Low levels of stem lodging occurred in the MT95 experiment and lodging was most frequent in the 1HN1 treatment. However, an analysis of lodged and upright plants from the 1HN1 treatment found no significant differences for a range of canopy and stem base parameters. The lodged plants did have slightly narrower basal diameters and stem wall widths caused by stem base disease.

Two commercial fields of winter wheat cv. Hussar, near Ross, Herefordshire were visited in late July 1995. The early sown Hussar crop had extensive lodging (approximately 75% field lodged), whereas the late sown Hussar crop had no lodging. An analysis of plants from both fields revealed only one significant difference: the early sown crop was 5 cm taller ($p<0.01$) than the late sown crop. On close examination of the lodged areas, failure was due entirely to stem buckling of the basal internodes. Some stem buckling was associated with stem base disease, but in most cases stems buckled naturally, often at soil level against dry, hard soil. Basal stem parameters were measured and showed no significant differences, although the early sown crop had 7% and 22% narrower basal diameters and stem wall widths respectively, and a 47% lower stem bending strength than the later sown crop.

Table 5.46 An analysis of lodged and upright plants in the MT96 experiment.

(1HN1 treatment)	Lodged plants	Upright plants
Canopy characteristics		
Plant height (m)	0.83	0.86
Plant shoot number	2.6	2.6
Ear area (cm^2)	5.5	6.2
Root characteristics		
Crown depth (mm)	15	18
Crown root number	17	20
Av. root cone diameter (mm)	36	41
Soil characteristics		
Soil strength (kPa) 25 mm	19	25
Soil moisture %	26	20

The analysis of lodged and upright plants from treatment 1HN1 in the MT96 experiment (Table 5.46), indicated that upright plants had slightly deeper crowns and better crown root structure which, in combination with being situated in areas of slightly stronger soil, may have prevented root lodging. It should be noted that all lodging in the MT96 experiment occurred after periods of rainfall. The first lodging event (June 11) occurred after 6 mm rainfall and low wind speeds (av. 2.5 m/s).

6. RESULTS : THE MODEL FINDINGS

Section 6.1 of this chapter describes how data from the field experiments were captured and used in the model. The next section (6.2) describes how the model is run using the computer 'lodging probability' program, and section 6.3 reports a sensitivity analysis which investigated the relative influence on lodging risk of each input parameter for the model. Section 6.4 describes how the model was 'test-run' to determine the lodging risk of plots in the MT95 and MT96 experiments, using data collected from the lodging risk period. In section 6.5, the effects of different agronomic treatments on lodging risk were assessed, and section 6.6 investigates the critical model parameters used. Finally, in section 6.7, a brief comparison is made of the lodging risk schemes and guidelines which are currently available.

6.1 Model data capture

The measurements made of the lodging risk parameters came from average values from ten plants. Use of the 10-percentile or the 90-percentile value calculated from the ten plants was considered. Depending on the lodging risk parameter being measured, either the 10 or 90-percentile would give a good indication of the value of the least or greatest 'lodging risk' plants. For example, for the centre of gravity, the 90-percentile represented the greatest lodging risk, but for crown root number, the 10-percentile represented the greatest lodging risk. Percentile values for some important model parameters (giving an indication of the amount of within plot variation) have been calculated in Table 6.1 below:

Table 6.1 Comparison of average values vs. percentile values for various important parameters.

Risk parameters (1HN3 treatment)	Average value	10-percentile value	90-percentile value
Natural frequency (Hz)	0.85	0.67	-
Centre gravity (m)	0.40	-	0.45
Shoot number	2.1	-	3.2
Root cone diameter (mm)	27.8	17.0	-
Crown root number	8.2	5.0	-

NB: Data from MT95 experiment at GS 69.

This approach was not investigated in this thesis mainly because predictions based on the mean plant values avoided any effects of treatment on character distribution (i.e. the natural variation of characters between plants). Another consideration was that using percentile values in the model would basically scale the results, producing higher lodging risks, which 'in practice' may give a more realistic estimate of the chance of lodging in a given field situation. It would be useful to investigate this further in the future. Another problem was that to fully investigate percentiles, all measurements must be carried out on the same identifiable plant, so that the correlation of one measurement in relation to another can be determined. Due to the large number of plants sampled, and the large number of measurements taken on each plant, measurements performed in the field (such as natural frequency) were not linked to measurements performed on the same plants in the laboratory. For this reason, it was also better to use mean values, as percentiles could lead to over-estimated results. However, consideration should be given to the implications that the taller, weaker stemmed and/or weaker anchored plants in an area of crop could be the focal point of a lodging event, which could then lead to further lodging due to a 'domino' type effect. For this reason, it could be useful in the future to look at variation between plants as discussed above.

It should also be noted that only the main stems were used for measurements of all the ten plant sample data. The main stem was used for two main reasons, firstly, time and labour constraints prevented measurement of all shoots in the ten plant sample, and secondly, selection of main stems reduced variability in the data. Since main stems tend to be slightly taller and heavier than tillers, it is likely that these model calculations will slightly overestimate base bending moments and lodging risks of whole plants. However, this effect is not thought to be large. The restrictions to using means and main stems were imposed as the initial 'ground rules' for model calibration.

6.2 Lodging risk program : use of the model

The risk model is currently used in conjunction with the important model parameters to predict lodging risk for a day in July, at the actual likely time of lodging events.

One of the main purposes of this thesis is, through using the model, to identify the relative importance of plant and soil characteristics studied to determine lodging risk. Also, by identifying the way agronomic factors affect these lodging risk characteristics, the model can be used to reveal how agronomic factors affect the chance of lodging occurring.

Simplified steps are described below which show how the lodging model program was run. These steps describe the state of the model when it was used for the sensitivity analysis.

	Step (subroutine in lodging model)	*State of model (at April 1996)*
1	Set fixed parameters	Complete
2	Input site wind exposure parameters	Complete
3	Input site rainfall parameters	Complete
4	Input soil parameters	In development
5	Input predicted plant parameters for July	From work of P.Berry
6	Determine wind speed probability distribution	Complete
7	Determine soil moisture probability distribution	In development
8	Start Monte Carlo procedure	Complete
9	Obtain realisation of wind speed	Complete
10	Obtain realisation of soil moisture	Complete but depends on 7
11	Calculate natural frequency for realised soil moisture	In development
12	Calculate stem base bending moment for realised conditions	Complete
13	Calculate stem failure moment for realised conditions	Complete
14	Calculate root failure moment for realised conditions	Complete
15	Check for root or stem lodging for realised conditions	Complete
16	Update root and stem lodging probabilities	Complete
17	Repeat steps 9 to 16 for 1000 realisations	Complete
18	Print lodging probabilities	Complete

It should be noted that step 5 above will eventually be determined by plant measurements made early in the spring which act as good predictors of what the likely parameter values (required by the model) will be during July (Berry, unpublished). Work done here by the author has established the range of values that these parameters can vary by during the July period, given different crop structure due to different husbandry. It is important to recognise at this stage that:

1. the model is still being developed, and at the time of submission the model had been further developed but, the April 1996 version was used here.

2. this section relates to the state of the model (as described in Chapter 3) when it was used for the sensitivity analysis which follows.

6.3 Sensitivity analysis of model parameters

The model was used in a parametric investigation to determine its sensitivity to and hence the importance of the various input parameters. The following set of default or standard parameters were defined and used as normal values for each sensitivity analysis (all based on measurements taken at ADAS Rosemaund, see below for details):

$V_{50} = 4$ m/s	$I_{50} = 3$ mm	$N = 3$	$\sigma = 50$ MPa	$s_0 = 15$ kPa
$V_{99} = 14$ m/s	$n_o = 1$ Hz	$a = 1.2$ mm	$D = 20$ mm	$m = 0.4$
$H = 100$ m	$X = 0.4$ m	$w = 0.5$ mm	$l = 20$ mm	

NB: See Engineering Model Codes for all the above definitions. Values for all other model parameters can be found in Chapter 3.

For these standard conditions, the probability of stem lodging, P_S, was calculated to be 0.024 (2.4%), and the probability of root lodging, P_R, was calculated to be 0.038 (3.8%), giving a total probability, P_T, of 0.062 (6.2%). The model was then run, varying each of the listed input parameters in turn, keeping the other input parameters set at the standard default values. It is worth noting that the model adopted a simple two stage definition of soil saturation (wet or dry), so that any variation in lodging probabilities was not totally smooth, but rather occurred in small step-type changes. Since these sensitivity tests were conducted, the model has been further developed in this area and the saturation status of the soil is now calculated on a continuous sliding scale, resulting in smoother changes in predicted lodging probabilities. The results of these sensitivity analyses can be seen in Figs 6.1-6.4.

The sensitivity analysis performed was crucially dependent on the ranges chosen for the inputs. The range of values used for each model parameter was chosen on the following basis; field altitude, H, ranged from 50-150 m, with a standard value of 100 m, which was just above the field altitude of the experiments at ADAS Rosemaund. The range of values for the meteorological parameters V_{50}, V_{99}, and I_{50} were from the work of Baker (1995). It should be noted that subsequent measurements of both mean hourly wind speeds, V_{50}, and extreme hourly wind speeds, V_{99}, in the field experiments, indicated that the standard values used (4 m/s and 14 m/s respectively) may be too high for average July conditions. Measurements taken in the field experiments at ADAS Rosemaund during July indicated that average wind speeds were between 1.5-2.0 m/s, with maximum wind speeds between 5-8 m/s on occasions (some of which coincided with lodging events).

The ranges of values used for all the plant parameters (Table 6.1) were chosen early in the project before all the results were collated, based on 'best knowledge' at the time and preliminary field measurements on the cv. Mercia at ADAS Rosemaund in 1994. The sensitivity analysis was then carried out and, when field results were fully collated over the three experimental years, some differences occurred between the ranges originally chosen for the sensitivity analysis and what was actually measured (Table 6.2). These slight differences were not important because the predicted lodging risks had already flattened out (reached a maximum or minimum) in all cases (see Figs 6.1-6.4). Natural frequency, n_0, ranged from 0.5-1.5 Hz, which represented the large variation produced from different agronomic treatment combinations for Mercia. For example, the range of values measured for n_0 during July in each experimental year was 0.65-1.25 Hz (MT94), 0.7-1.35 Hz (MT95) and 0.55-1.1 Hz (MT96). Value ranges for centre of gravity height, X, and plant shoot number, N, were also taken from the field measurements. Stem base radius, a, ranged from 0.8-1.6 mm which accurately represented the variation which occurred for the cv. Mercia. Stem wall width, w, ranged from 0.25-0.75 mm with a standard value of 0.5 mm. Further measurements of w have indicated that variation is slightly less (0.45-0.75 mm), with a standard value of 0.6 mm more accurately representing the cv. Mercia. Stem failure stress, σ, ranged from 20-70 MPa and a standard value of 50 MPa was set on the basis of a few, very preliminary measurements. Further, more detailed results have shown that the above range is slightly too high, and between 15-55 MPa with a standard value of 35 MPa more accurately represents the variation for the cv. Mercia. Agronomic variation in root cone diameter, D, is large, resulting in the range from 10-40 mm. Root cone diameters in the MT94 experiment were as small as 10 mm (HSR), but averaged between 20-30 mm in the MT95 experiment. However, results from the MT96 experiment, where rooting was good, have shown root cone diameters up to 50 mm for the cv. Mercia. Structural rooting depth ranged from 10-50 mm which represents well the variation in this parameter due to drilling depth, root growth and soil structure. Soil porosity, m, ranged from 0.2-0.6 which represented the range of values for clay soils to sandy soils (ADAS, 1982). Variation in soil strength between wet and dry soils was large, between 10-100+ kPa under field conditions. The ranges of values described in Table 6.2 are likely to well illustrate the likely ranges found in the UK wheat crop because measurements were taken from 20 different varieties (VT95) and over three seasons (differing in their effect on crop growth and development) for the cv. Mercia.

Table 6.2 Comparison of plant character ranges measured over three experimental seasons with the range used for the sensitivity analysis.

Character	1993-94	1994-95	VT95	1995-96	Sensitivity range
Natural freq. (Hz)	0.59-1.22	0.81-1.41	0.71-1.00	0.56-1.13	0.5-1.5
Centre gravity (m)	0.41-0.58	0.36-0.59	0.32-0.45	0.37-0.61	0.3-0.5
Shoot number	2.0-4.4	1.7-3.7	1.7-2.8	2.1-5.7	1.0-5.0
Stem radius (mm)	1.61-2.36	1.47-1.82	1.67-2.16	1.33-1.84	0.8-1.6
Stem wall width (mm)	-	0.54-0.64	0.56-0.92	0.41-0.75	0.25-0.75
Stem failure moment	-	-	-	25-54 MPa	20-70
Root cone diam. (mm)	-	17-45	19-47	28-58	10-40
Rooting depth (mm)	-	27-32	-	29-59	10-50

NB: The range of values come from measurements made in mid-July (GS69-72).

Sensitivities to the model input characteristics are shown in Fig. 6.1. It can be seen from these results that with increasing severity of site and meteorological conditions, such as H, V_{50} and V_{99}, there was an increase in total lodging probabilities, as would be expected. Lodging risk was also increased by an increase in average daily rainfall (I_{50}), with P_R being more affected than P_S by changes in I_{50}. P_S was generally more affected by changes in wind conditions. Sensitivities to model input canopy characteristics are shown in Fig. 6.2. As plant natural frequency decreased the probability of lodging increased, with both P_S and P_R affected similarly. The variation of lodging risk predicted for natural frequency was higher than all other canopy characteristics, indicating the importance of this parameter. Increases in the centre of gravity and plant shoot number also increased lodging risk. Sensitivities to stem base characteristics are shown in Fig. 6.3. As the relative material strength or stem failure stress increased the lodging risk decreased, and at the same time P_R became more predominant than P_S. For low values of stem failure stress, of stem base radius and of stem wall width, P_S increased greatly and P_R was not affected. Sensitivities to root and soil characteristics are shown in Fig. 6.4. The model predicted the greatest variation due to root cone diameter, which indicates that this is the most influential below-ground parameter in the root lodging process. Root lodging was affected most with a predicted P_R of over 25% at the lowest value (10 mm). Lodging risk decreased as the structural rooting depth increased, with P_R more predominant at a shallow rooting depth. From the results, it can be seen that changes in soil parameters primarily affected root lodging probabilities as expected. P_R decreased as both soil porosity and soil shear strength increased. The model predicted that P_R was more predominant at low soil strengths (5-20 kPa), but as soil strength increased above 25 kPa, stem lodging became predominant. No root lodging was predicted once the soil strength reached 40 kPa and above. It should be noted that when both stem and root lodging occur equally, root lodging is 'counted' by the model. The standard values used in the sensitivity analysis were in general considered to be well representative of measured field values at Rosemaund in 1994-96. However, from later field measurements, the value of dry soil strength (s_0) was considered to be too low. The default value of 15 kPa (Baker, 1995) was equivalent to extremely wet field conditions and was originally chosen from soil strength work by Crook & Ennos (1993), where highly saturated soil conditions were used which were found to be unrealistic under field conditions. This is likely to have caused model results to more frequently predict root lodging.

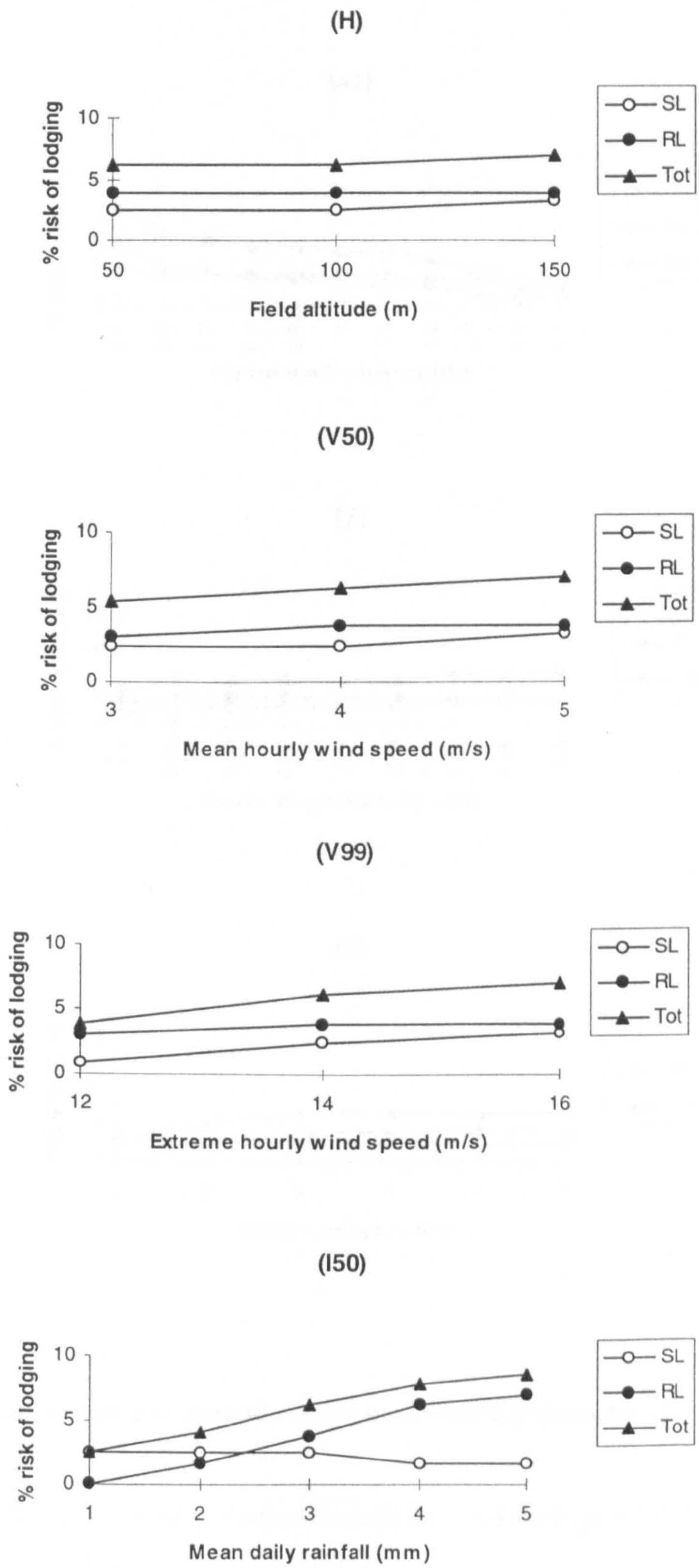

Fig. 6.1. Sensitivity analysis for the model site characteristics.

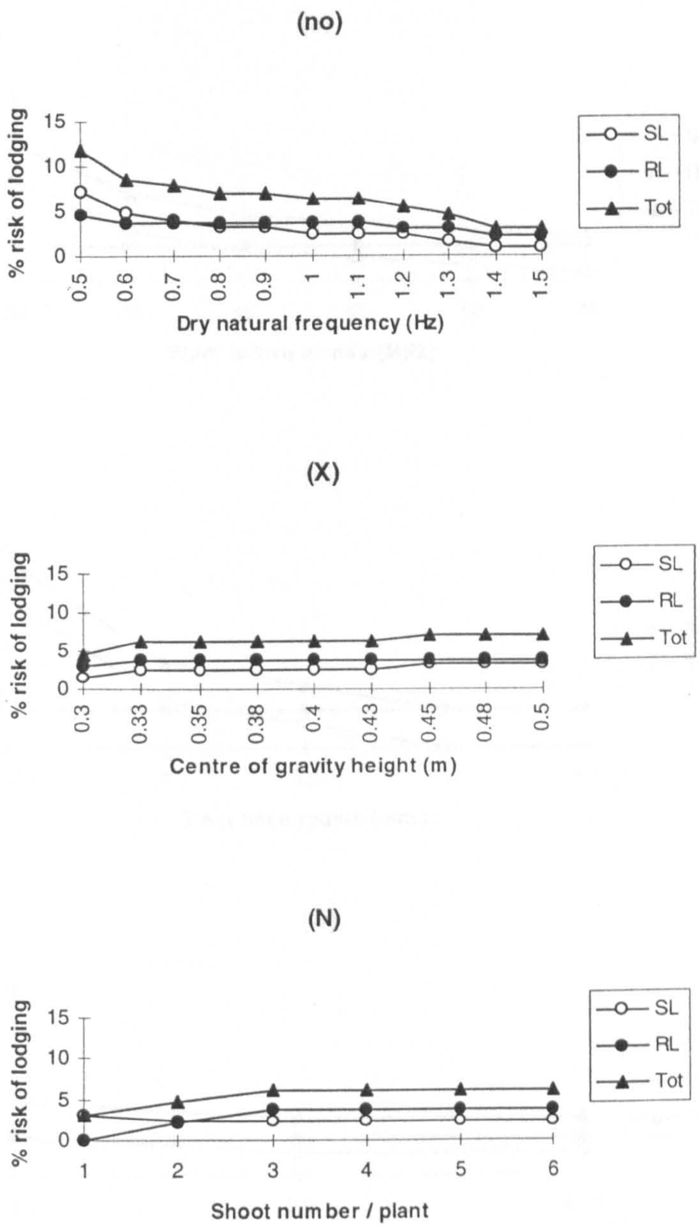

Fig. 6.2. Sensitivity analysis for the model canopy characteristics.

The following legend definitions should be noted for Figs 6.1-6.4; SL = stem lodging, RL = root lodging and Tot = total lodging.

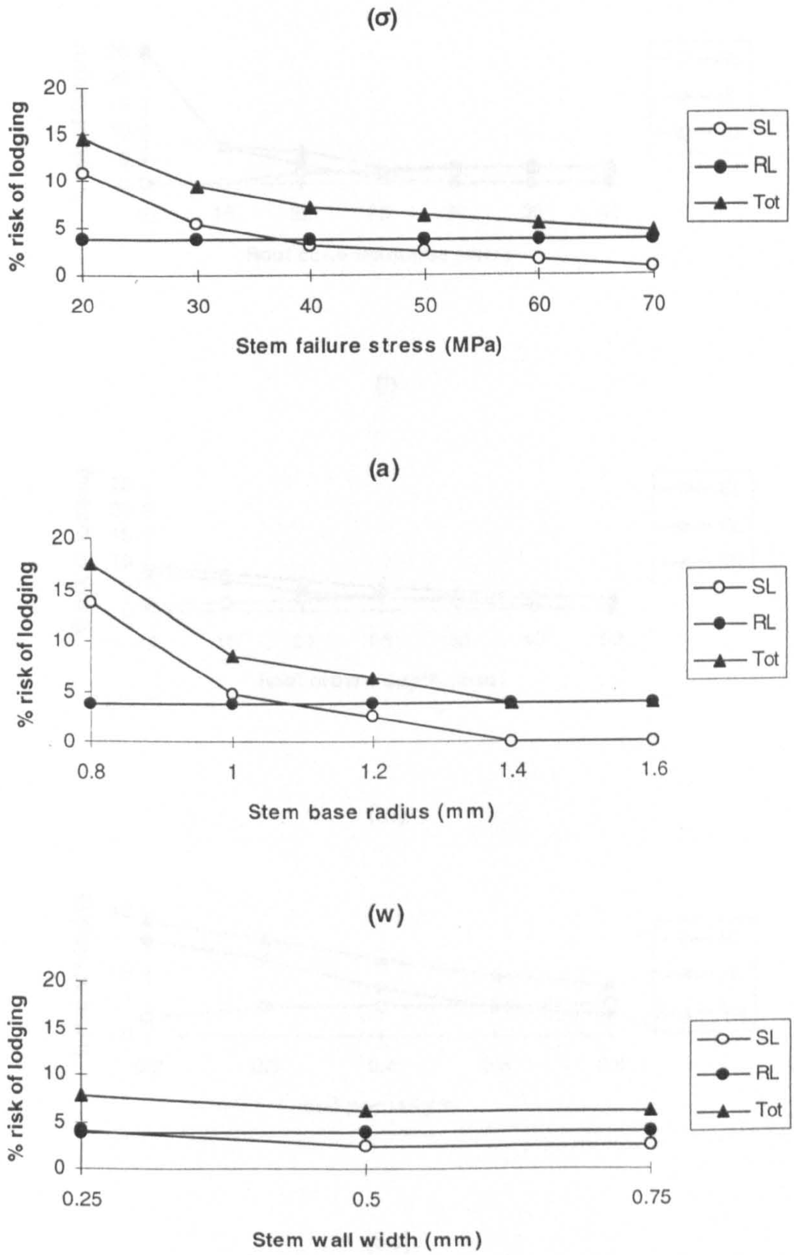

Fig. 6.3. Sensitivity analysis for the model stem base characteristics.

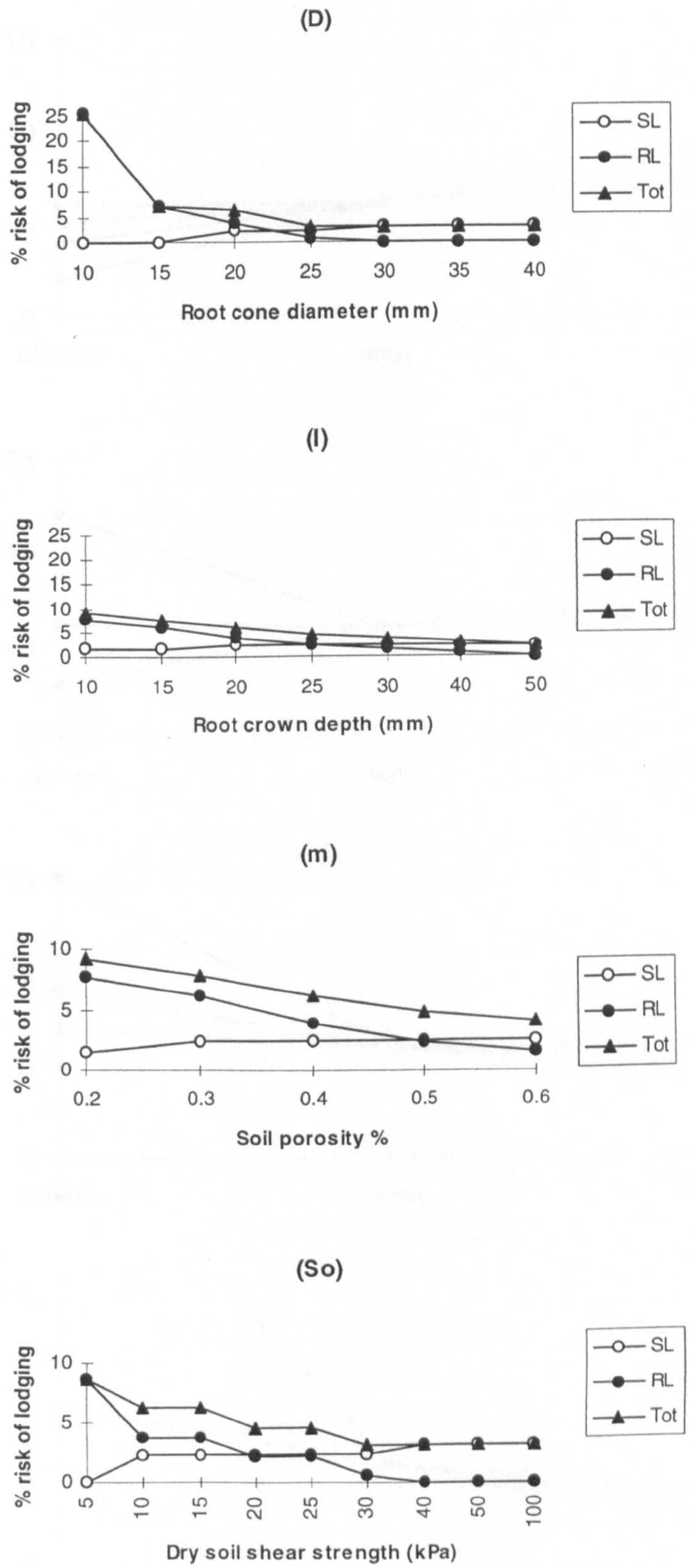

Fig. 6.4. Sensitivity analysis for the model root and soil characteristics.

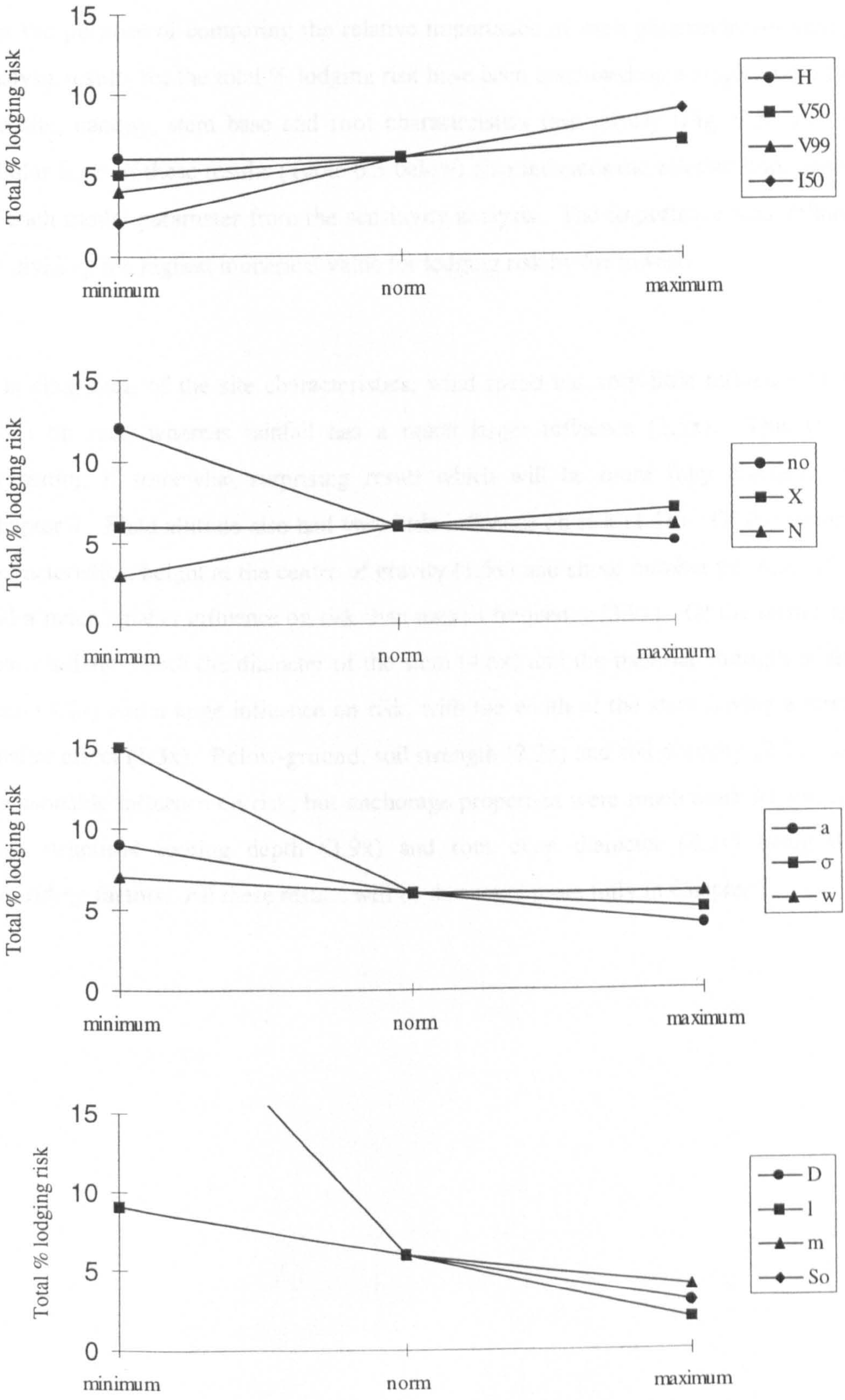

Fig 6.5. Comparison of sensitivity analyses for all model parameters.

6.3.1 *Summary of model sensitivity analysis*

For the purpose of comparing the relative importance of each parameter, sensitivity analysis results for the total % lodging risk have been combined on a single graph for the site, canopy, stem base and root characteristics respectively (Fig. 6.5a-d). A tabular form of these results (Table 6.3 below) also indicates the relative importance of each model parameter from the sensitivity analysis. The importance was defined by dividing the highest numerical value for lodging risk by the lowest.

It is clear that, of the site characteristics, wind speed has very little influence (1.3-1.8x) on risk, whereas rainfall has a much larger influence (3.5x). This is an interesting if somewhat surprising result which will be more fully discussed in Chapter 7. Field altitude also had very little influence on risk (1.1x). Of the canopy characteristics, height at the centre of gravity (1.5x) and shoot number per plant (2x) had a much smaller influence on risk than natural frequency (3.9x). Of the stem base characteristics, both the diameter of the stem (4.6x) and the material strength of the stem (3.2x) had a large influence on risk, with the width of the stem having a much smaller effect (1.3x). Below-ground, soil strength (2.2x) and soil porosity (2.3x) had a reasonable influence on risk, but anchorage properties were much more important, with structural rooting depth (3.9x) and root cone diameter (8.2x) being the overriding factors. All these results will be discussed more fully in Chapter 7.

Table 6.3 Summary of the sensitivity analysis showing the relative importance of each model parameter.

	Minimum	Norm	Maximum	Importance
Altitude (m)	50	100	150	
lodging risk	6.2	6.2	7.0	1.1x
Av. wind speed (m/s)	3	4	5	
lodging risk	5.4	6.2	7.0	1.3x
Extreme wind speed (m/s)	12	14	16	
lodging risk	3.8	6.2	7.0	1.8x
Av. daily rainfall (mm)	1	3	5	
lodging risk	2.4	6.2	8.5	3.5x
Natural frequency (Hz)	0.5	1.0	1.5	
lodging risk	11.7	6.2	3.0	3.9x
Centre of gravity height (m)	0.3	0.4	0.5	
lodging risk	4.6	6.2	7.0	1.5x
Shoot number per plant	1	3	5	
lodging risk	3.1	6.2	6.2	2.0x
Stem base radius (mm)	0.8	1.2	1.6	
lodging risk	17.6	6.2	3.8	4.6x
Stem wall width (mm)	0.25	0.5	0.75	
lodging risk	7.8	6.2	6.2	1.3x
Stem failure stress (MPa)	20	50	70	
lodging risk	14.6	6.2	4.6	3.2x
Root cone diameter (mm)	10	20	40	
lodging risk	25.5	6.2	3.1	8.2x
Structural root depth (mm)	10	20	50	
lodging risk	9.3	6.2	2.4	3.9x
Soil strength (s_o)	5	15	25	
lodging risk	8.6	6.2	4.0	2.2x
Soil porosity (m)	0.2	0.4	0.6	
lodging risk	9.3	6.2	4.0	2.3x

6.4 Lodging risk prediction

This section primarily aims to present a simple comparison of the experimental treatments by running the 'risk' model for each plot using data collected from the field experiments during July. This will enable the agronomic factors tested in the treatments to be assessed and compared for their influence on lodging risk. It will also enable a degree of model calibration and an initial test of the model accuracy, in terms of predicted versus actual results.

The model analysis for the 32 treatments (96 plots) required a number of standard model parameters because data were not available for each plot. These were as follows; V_{50} (4 m/s), V_{99} (14 m/s), I_{50} (3 mm), H (100 m), l (20 mm), m (0.4%) and s_0 (15 kPa). Two further parameters were standard for the MT95 experiment due to lack of data; w = 0.51 mm (HSR) and 0.63 mm (LSR), σ = 42 MPa (HSR) and 46 MPa (LSR) (see Model Engineering Codes for definitions). The variable parameters measured separately for each treatment were; n, X, N, a, w (except MT95), σ (except MT95) and D. Individual plot data for the variable parameters were taken during July, the expected greatest lodging risk period. Table 6.4 below shows the results of this comparison for both the MT95 and MT96 experiments.

The highest risk treatment for both the MT95 and MT96 experiments was the early sown, high seed rate, high residual N, NIL 'control' treatment (1HN1). The total risk predicted for MT96 (12%) was over twice that for MT95 (5%), although it is worth noting that root lodging risk (albeit small) was predicted in MT95 but not in MT96 (nor was it for any other treatments). This is a somewhat surprising result as the lodging which occurred in the MT96 experiment was predominantly caused by root failure. The implications of this observation will be discussed more fully in Chapter 7. For both MT95 and MT96, all treatment combinations which were late sown and low seed rate had zero predicted risk. In general, the treatments with the higher predicted risks seemed well in line with those treatments which lodged in the field (see section 5.5). It is important to note that no formal statistics were done on the results in Table 6.4, mainly due to the very high number of zero values produced and the nature of 'risk values' themselves. For this reason, some caution should be applied when comparing risks presented in tables throughout this Chapter.

Further work which would be useful when the model is more fully developed would be to repeat this test of the accuracy of the lodging risk model by running the model using data collected from the field during July (see section 5.5), and then analysing the model probabilities generated for different treatments. This would enable the agronomic factors tested in treatments to be assessed for their effects on lodging risk.

It would also enable further calibration of the model, if predicted results were compared to the lodging which occurred in the MT96 experiment.

Table 6.4 Model predicted lodging risk per treatment in experiments MT95 and MT96.

Treatment	*% risk* SL		*% risk* RL		*% risk* Total	
	MT95	MT96	MT95	MT96	MT95	MT96
1HN1	4	12	1	0	5	12
1HN2	1	6	0	0	1	6
1HN3	1	0	0	0	1	0
1HN4	3	4	0	0	3	4
1HO1	2	1	0	0	2	1
1HO2	0	1	1	0	1	1
1HO3	0	0	0	0	0	0
1HO4	2	3	1	0	3	3
1LN1	0	6	0	0	0	6
1LN2	0	3	0	0	0	3
1LN3	0	0	0	0	0	0
1LN4	0	2	0	0	0	2
1LO1	0	0	0	0	0	0
1LO2	0	2	0	0	0	2
1LO3	0	0	0	0	0	0
1LO4	0	0	1	0	1	0
2HN1	2	0	0	0	2	0
2HN2	1	0	0	0	1	0
2HN3	0	0	0	0	0	0
2HN4	3	0	1	0	4	0
2HO1	0	0	1	0	1	0
2HO2	0	0	0	0	0	0
2HO3	0	0	0	0	0	0
2HO4	2	0	0	0	2	0
2LN1	0	0	0	0	0	0
2LN2	0	0	0	0	0	0
2LN3	0	0	0	0	0	0
2LN4	0	0	0	0	0	0
2LO1	0	0	0	0	0	0
2LO2	0	0	0	0	0	0
2LO3	0	0	0	0	0	0
2LO4	0	0	0	0	0	0

NB: For each treatment, the result is an average value from 3 plots and is rounded to the nearest 1%, where SL = stem lodging and RL = root lodging.

6.4.1 *Key findings from model validation studies*

Comparing the final crop lodging scores (section 5.5) between the MT95 and MT96 experiments, it is clear that lodging was much more prevalent in the MT96 experiment. In order to identify whether more lodging occurred in the MT96 experiment due to differences between the crops or the weather or both, model specific data relating to the plant canopy, stem base and root structural characteristics were analysed using the model. This was done for two contrasting treatments in the field experiments, and for both seasons in question. The results produced by the model (Table 6.5) clearly show that the aerial forces (base bending moment, B) produced on both the plant and shoot due to a high wind gust in the MT96 experiment, were nearly twice as much as in the previous MT95 experiment for the early sown, high seed rate, high residual N and NIL PGR treatment (1HN1). It can also be seen that the root failure moment (B_R) in MT96 was much lower (approximately 2.5x) than in the previous MT95 experiment for the 1HN1 treatment (which lodged by stem failure in 1995 and by root failure in 1996).

Table 6.5 The aerial force imposed on the plant base compared to the stem and root failure moment for two contrasting treatments in the MT95 and MT96 experiments.

Treatment	B shoot (Nm)	B plant (Nm)	B_S (Nm)	B_R (Nm)
MT95				
1HN1	0.017	0.037	0.086	0.229
2LO3	0.015	0.054	0.165	0.526
MT96				
1HN1	0.029	0.076	0.062	0.089
2LO3	0.013	0.063	0.166	0.570

NB: Base bending moments were calculated using weather conditions during the lodging event and the nearest possible plant measurements (GS 72).

This provides good evidence to suggest that the 'state of the plant' is critical in determining lodging risk, with a taller, larger, heavier and more lodging prone crop canopy being produced in MT96 experiment. This is likely to have been the predominant factor, but the weather and soil conditions are also likely to have had some effect too, with several heavy rain showers (causing the surface soil to become moist/wet) preceeding the lodging events in 1996. It should be noted that although the MT96 experiment has been modelled in this chapter, model development and testing was not based on the 1996 data set.

6.5 Effects of major agronomic factors on plant characters and lodging risk

The results set out below show just the main effects of the agronomic treatments imposed in each experimental year on lodging risk i.e. sowing date, seed rate, residual nitrogen and lodging control.

In the 1994-95 season, the early sown crop had only a marginally greater predicted lodging risk than the late sown crop (Table 6.6). However, in the 1995-96 season a bigger difference was evident (as expected), with the early sown crop having a 4.7% greater predicted lodging risk than the late sown crop.

Table 6.6 The effect of sowing date on predicted lodging risk.

Sowing date		*Early (Sept.)*		*Late (Oct.-Nov.)*	
Experiment		MT95	MT96	MT95	MT96
Height (m)		0.91	0.92	0.94	0.86
Natural frequency (Hz)		0.99	0.74	1.00	0.91
Centre of gravity (m)		0.41	0.47	0.41	0.42
Plant shoot number		2.6	3.4	2.7	4.2
Stem failure stress (MPa)		(S)	37	(S)	39
Crown root number		9.1	23.8	10.8	25.5
Root cone diameter (mm)		22.3	37.3	25.3	44.5
Model predicted	*stem*	2.4	10.9	2.4	6.2
% lodging risk	*root*	2.2	0.0	0.7	0.0

NB: (S) denotes where a standard value has been used.

In both the 1994-95 and 1995-96 seasons stem lodging probabilities were the same for both levels of seed rate (Table 6.7). Although less predominant, root lodging risk was highest in the high seed rate crop in the MT95 experiment. It should be noted that plant numbers were lower in the MT96 experiment.

Table 6.7 The effect of seed rate on predicted lodging risk.

Seed rate		*High (500 seeds/m²)*		*Low (250 seeds/m²)*	
Experiment		MT95	MT96	MT95	MT96
Height (m)		0.92	0.88	0.93	0.90
Natural frequency (Hz)		0.98	0.79	1.01	0.86
Centre of gravity (m)		0.41	0.44	0.41	0.44
Plant shoot number		2.0	2.9	3.2	4.5
Stem failure stress (MPa)		(S)	39	(S)	38
Crown root number		8.3	21.3	11.6	28.0
Root cone diameter (mm)		20.6	37.4	27.0	44.5
Model predicted	*stem*	2.4	6.9	2.4	6.9
% lodging risk	*root*	2.2	0.0	0.7	0.0

In both experimental seasons, lodging probabilities were not affected by different residual N levels (Table 6.8); however, probabilities for stem failure were higher than for root failure. Overall, lodging risk was higher in the MT96 experiment.

Table 6.8 The effect of residual nitrogen on predicted lodging risk.

Residual nitrogen		*High (330-350 kgN)*		*Low (30-50 kgN)*	
Experiment		MT95	MT96	MT95	MT96
Height (m)		0.93	0.90	0.92	0.88
Natural frequency (Hz)		0.99	0.81	1.00	0.84
Centre of gravity (m)		0.42	0.45	0.40	0.44
Plant shoot number		2.7	3.8	2.5	3.8
Stem failure stress (MPa)		(S)	38	(S)	39
Crown root number		10.1	23.7	9.8	25.6
Root cone diameter (mm)		24.1	40.2	23.5	41.7
Model predicted	*stem*	2.4	6.9	2.4	6.9
% lodging risk	*root*	1.4	0.0	1.4	0.0

In both seasons, the NIL 'control' had a greater overall lodging risk probability than the other control treatments (Table 6.9). Also, the application of PGRs reduced lodging probabilities (5C+T the most), while lodging probabilities for the G5 treatments were higher than for 5C treatments but lower than NIL 'control' treatments. Total lodging risk was approximately twice as high in the MT96 experiment. Clearly, the addition of the PGR Terpal, further reduces plant height and the centre of gravity (compared to chlormequat PGR alone), which combine to cause a higher natural frequency: an important aspect in reducing the lodging risk of this treatment combination.

Table 6.9 The effect of lodging control on predicted lodging risk.

Lodging control	*NIL*		*5C*		*5C+T*		*G5*	
Experiment (MT)	(95)	(96)	(95)	(96)	(95)	(96)	(95)	(96)
Height (m)	1.01	0.96	0.91	0.87	0.83	0.82	0.95	0.92
Natural frequency(Hz)	0.86	0.72	1.07	0.87	1.18	0.93	0.86	0.79
Centre of gravity (m)	0.45	0.48	0.40	0.43	0.37	0.41	0.41	0.45
Plant shoot number	2.9	4.0	2.6	3.6	2.6	4.1	2.5	3.5
Stem fail. stress (MPa)	(S)	40	(S)	36	(S)	39	(S)	39
Crown root number	10.0	26.2	10.0	23.8	9.8	23.8	10.0	24.0
Root cone diam. (mm)	24.1	41.9	23.3	39.7	24.2	39.7	23.6	41.3
Predicted *stem*	3.2	9.3	2.4	6.9	1.6	6.9	3.2	6.9
% risk *root*	2.2	0.0	0.7	0.0	0.0	0.0	1.4	0.0

6.6 Investigation of areas for further model development

The sections below describe some further areas of work (which may help future model development) based on preliminary findings from this thesis.

6.6.1 *The 'lodging risk' period*

This section investigates the seasonal variation of two critical plant characters (natural frequency and stem base failure moment), which were found in earlier sections to be important in terms of lodging risk. A much more detailed examination of seasonal variation in all important plant characters can be found in the Ph.D. thesis by Berry (unpublished).

In the ST94 experiment, natural frequency was found to decrease across all treatments following a period of rainfall in July after a prolonged dry spell, which wetted both the crop canopy and the soil. For the early sown crop, natural frequency decreased from an average of 0.78 Hz to 0.70 Hz and for the late sown crop, natural frequency decreased from an average of 1.17 Hz to 0.88 Hz. In the MT95 experiment, natural frequency was measured weekly from mid-May, the completion of stem extension, to early August (pre-harvest), for two contrasting treatments; 1HN3 and 2LO3 (see Treatment Codes).

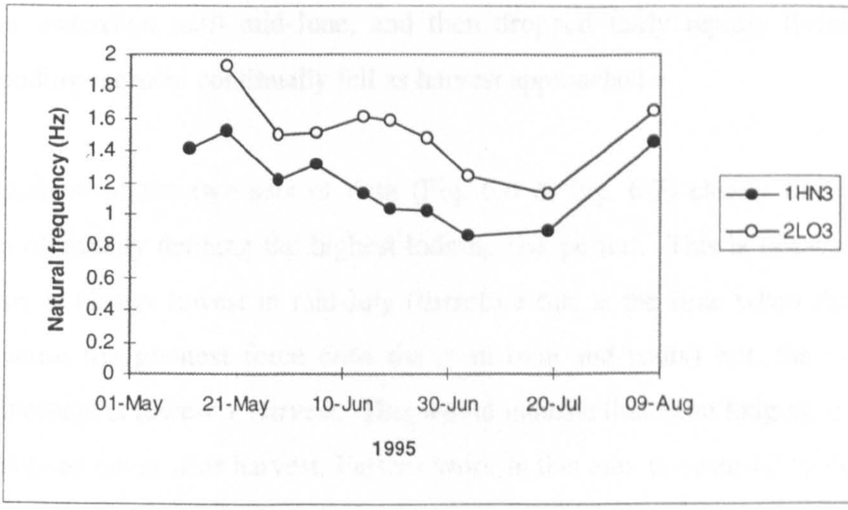

Fig 6.6. The pattern of natural frequency through the season for two contrasting treatments in the MT95 experiment.

Fig. 6.6 above shows that for both treatments natural frequency fell steadily from full stem extension (mid-May) and was lowest in mid-July, coinciding with the expected highest lodging risk period. The early sown, high seed rate, high residual nitrogen treatment consistently had a lower natural frequency, representing a higher lodging risk. For both treatments, the data clearly show that natural frequency varies throughout the lodging risk period.

The first lodging event in the MT96 experiment occurred on 11 June and natural frequencies were between 0.85-0.90 Hz for the treatments which lodged. At the end of June, two weeks after the first lodging event, natural frequency, soil shear strength and soil moisture were measured on a small subset of treatments (still under moist soil conditions). Natural frequency, soil strength and soil moisture ranged from 0.64-1.02 Hz, 22-41 kPa and 19-21% respectively. These results indicate that during this period the crop had low natural frequencies, in combination with fairly weak and wet soil, which may have predisposed the crop to root lodging.

The same contrasting treatments used to record the seasonal pattern of natural frequency were used to measure stem base failure moments through the season. The data shown in Fig. 6.7 have been averaged over the three lowest (basal) internodes for each treatment. For both treatments, stem failure moment increased initially from full stem extension until mid-June, and then dropped fairly rapidly through July. Stem bending moment continually fell as harvest approached.

A comparison of the two sets of data (Fig. 6.6 & Fig. 6.7) clearly illustrates the problem of exactly defining the highest lodging risk period. This is because natural frequency is clearly lowest in mid-July (therefore this is the time when the canopy would cause the greatest force onto the stem base and roots) but, the stem base failure moment is lowest at harvest. This would indicate that stem lodging is possibly more likely to occur near harvest. Further work in this area is essential to decide the most appropriate lodging risk period, which may need to be based on a longer period than for one day in July, as described in this work.

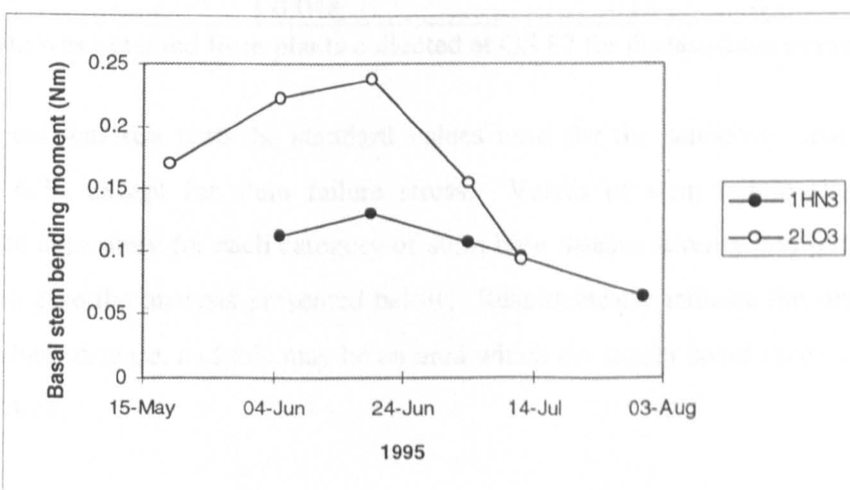

Fig 6.7. The pattern of the stem base failure moment through the season for two contrasting treatments in the MT95 experiment.

6.6.2 *Influence of stem base disease*

The results in Table 6.10 show how severe stem base diseases (Fusarium and sharp eyespot) both significantly reduced the stem failure moment, which resulted in a 27-40% greater predicted lodging risk than for uninfected stems.

Table 6.10 The effect of stem base disease on stem failure moment and predicted lodging risk in the MT95 experiment.

a) Fusarium, internode 2

Disease severity	Stem failure moment (Nm)	*% lodging risk*	
		stem	*root*
Clean	0.072	12	4
Slight	0.070	11	4
Moderate	0.065	12	4
Severe	0.040	15	4

b) Sharp eyespot, internode 2

Disease severity	Stem failure moment (Nm)	*% lodging risk*	
		stem	*root*
Clean	0.072	12	4
Slight	0.080	11	4
Moderate	0.061	15	4
Severe	0.048	17	4

NB: Data was obtained from plants collected at GS 87 for disease assessment.

The model was run with the standard values used for the sensitivity analysis (see section 6.3), except for stem failure stress. Values of stem failure stress were measured separately for each category of stem base disease severity and put into the model to give the analysis presented below. Results clearly indicate the importance of stem base disease, and this may be an area which the model could take account of in the future.

6.6.3 *Calculation of root failure moment*

Measurements of root failure moment were both difficult and time intensive, and very much dependent on field soil conditions. It was therefore not possible to investigate the seasonal variation of this parameter in the way that was done for natural frequency and stem base failure moment in section 6.6.1. However, some very useful data were collected during 1996 which are described below.

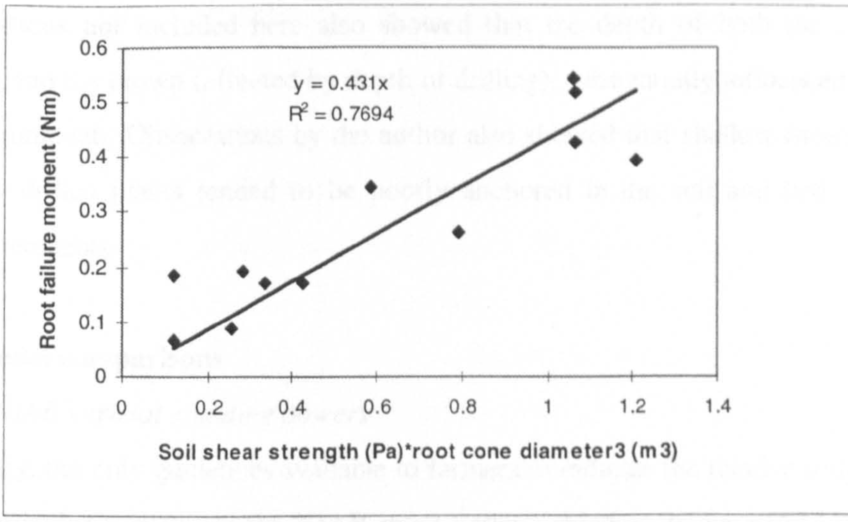

Fig 6.8. Investigation of below-ground factors affecting root failure moment in the MT96 experiment.

The hand-held torquemeter designed by Ennos and Crook (Manchester University), was used in the MT95 and MT96 experiments to provide field data of root failure moments under moist soil surface conditions. In the MT95 experiment, only very limited results were obtained due to the extremely dry and hard soil conditions during July. Results (Table 5.40) showed that the low seed rate crop had a significantly ($p<0.001$) greater (over 60%) root failure moment than the high seed rate crop, in both mid- and late-July. It should be noted that the topsoil was wetted to obtain these results (see section 4.2.5). However, in the MT96 experiment, more extensive results were obtained because soil conditions were moist and more applicable to use of the torquemeter. Root failure moment was plotted against soil shear strength multiplied by the cube of the root cone diameter (also measured in the field), derived from the root model expression of Ennos (1991). The resulting regression graph above (Fig. 6.8) indicates that the Ennos expression is good, but that the constant involved should be much lower. The field experiment results showed the constant had a value of 0.43 rather than 3.53 expressed by Ennos. The significance of this result will be discussed in detail later, see section 7.2.1.

Field results in the MT96 experiment showed a good relationship between the root failure moment and structural root/soil anchorage (Fig. 6.8). As root failure moment increased, both the root cone diameter and the soil strength increased. Field observations not included here also showed that the depth of both the structural rooting and the crown (affected by depth of drilling), substantially influenced the root failure moment. Observations by the author also showed that shallow rooted and/or shallow drilled plants tended to be poorly anchored in the soil and had low root failure moments.

6.7 Model comparisons

6.7.1 *NIAB varietal standing powers*

Currently, the only guidelines available to farmers to indicate the relative lodging risk of a particular variety are the NIAB rated varietal standing powers (NIAB, 1998). Results from the VT95 experiment (Table 6.11) showed that in general, the values of both root and stem failure moment increased as the NIAB standing power ratings of varieties increased, which indicates that overall the NIAB standing powers are reasonably accurate. For example, Hereward with a high standing power rating (8) had a much higher root and stem failure moment than all varieties with a lower standing power e.g. Cadenza or Beaver. The NIAB standing powers act as a guide but are limited in that they are very much focused on the stem (with 'straw length' ratings acting as another lodging 'indicator') and are based on visual assessments of plot lodging rather than quantitative measurements of stem strength and root strength.

Table 6.11 A comparison of NIAB rated varietal standing power against model calculated aerial force, stem base and root failure strengths in the VT95 experiment.

Variety/NIAB standing power		Whole plant base bending moment (Nm)	Root failure moment (Nm)	Main stem base bending moment (Nm)	Stem failure moment (Nm)
Little Joss	3-4	0.044	1.55	0.026	0.11
Beaver	6	0.032	-	0.014	0.10
Cadenza	6	0.025	0.86	0.016	0.13
Mercia	6	0.026	-	0.014	0.14
Rialto	6	0.024	1.56	0.014	-
Spark	7	0.050	1.91	0.018	-
Riband	7	0.021	2.10	0.014	0.15
Hereward	8	0.025	3.88	0.014	0.18

However, what NIAB ratings do not provide is a reason for a high or low standing power. Results from the VT95 experiment also indicate the relative strength of the stem base and the roots for each variety from the calculated stem failure moment and root failure moment respectively. For example, the low standing power rating (6) of the variety Cadenza is probably explained by the extremely low root failure moment, resulting from a poor root/anchorage structure. However, a very low stem failure moment for the variety Beaver, indicates that poor stem structure is the main reason for its low standing power rating. The advantage of this type of information is that it provides farmers with a better idea about which part of the plant to target in terms of lodging control. For example, it may be more important for a variety such as Cadenza to take measures to improve root/soil structure (such as lower seeding rates and rolling), whereas for Beaver, where stem structure is obviously weak, PGRs would be most beneficial. For a variety such as Hereward with both good stem and root structure, careful management combined with reduced PGR inputs should be sufficient to prevent lodging. The inclusion of the information shown in Table 6.11 in NIAB variety listings would provide the grower with much greater 'precision', and a better understanding of the reasons for varietal susceptibility to lodging. This would therefore enable farmers to make a more informed varietal choice.

6.7.2 *Star-rating lodging prediction schemes*

A number of 'star rating' or 'risk score' systems currently exist to guide farmers on their PGR decisions in the spring, such as the 3-Step PGR Decision Guide (BASF, 1995a) and the ADAS Winter Wheat Plant Growth Regulators Risk Assessment Chart (ADAS, 1996). The key factors to consider in both schemes are variety, site lodging history, drilling date, spring plant population, nitrogen rate and timing, yield potential and potential market. Scores or stars (*) are then assigned for each of these catergories. The main limitation of both these schemes is that they rely heavily on NIAB rated varietal standing powers. These are assumed to have the greatest influence on the risk scores. At present, both the NIAB standing powers and the 'risk scores' from such schemes are focused almost entirely on stem strength and stem based lodging problems. Another limitation of these schemes is that the remedial measures proposed are restricted to PGR applications, which may not completely solve the problem, and can only be used after the crop has already become lodging prone. The more interactive approach proposed in this work is very different to the current star rating schemes described above, in that, it provides a common absolute scale on which to assess lodging risk, it provides a mechanistic means of inter-relating all the different influences on lodging risk, and it allows revision of lodging assessments as each season unfolds. This has obvious advantages over the schemes described above which are much more retrospective and rely totally on PGRs to 'put the crop right', which will not be possible in many situations, especially where poor root structure is to blame for lodging.

The two PGR schemes described were further investigated by using them to calculate star ratings/risk scores for the various agronomic treatments in the field experiments (Table 6.12). For the BASF scheme, the results ranged from 8 stars (for the early sown, high seed rate, high residual N treatment) to 4 stars (for the late sown, low seed rate, low residual N treatment). According to the BASF scheme, 4 or more stars indicate that a full PGR programme should be applied, which amounts to 2.5 l/ha '5C Cycocel' (between GS 25-31) and upto 2.5 l/ha 'Terpal' (between GS 32-49).

Table 6.12 Results of PGR-use decision guides for treatments used in the field experiments at ADAS Rosemaund.

Treatment code	BASF scheme star score (*)	ADAS scheme risk score	Model predicted *% lodging risk*	% area lodged
1HN(1)	********	-2 to -3	12	93
1HO(1)	*******	-1 to -2	1	75
1LN(1)	******	0 to -1	6	82
1LO(1)	*****	0	0	43
2HN(1)	*******	-1 to -2	0	55
2HO(1)	*****	0 to +1	0	46
2LN(1)	*****	+1 to +3	0	12
2LO(1)	****	+3 to +5	0	8

For the ADAS scheme, only the 'expected' highest risk (1HN) and lowest risk (2LO) treatments were analysed, which had risk scores of between -2 to -3 and +3 to +5 respectively. According to the ADAS scheme, with a score of -2 to -3, cropping strategy should be investigated for the 1HN treatment in order to minimise lodging pressure. A score of +3 to +5 indicated medium to high risk of lodging for the 2LO treatment. The remedial action recommended by the ADAS scheme for these categories is 1.75 to 2.5 l/ha chlormequat (medium risk) and 2.5 l/ha chlormequat or 1.75 l/ha chlormequat followed by 1.5 l/ha Terpal or 0.5 l/ha Cerone. In summary, for the extremely wide range of lodging risk produced by the different agronomic treatments in the field experiments, the BASF scheme did not differentiate any treatments and indicated that full PGR programmes should be used for all. In contrast, the ADAS scheme indicated that the 'highest risk' treatment in the field experiments (1HN) was too prone to lodging even for a full PGR programme to control, although the 'lowest risk' treatment (2LO) was still given a medium to high risk of lodging. These results will be discussed further in Chapter 7.

6.7.3 *Commercial plant growth regulators*

Some manufacturers advocate that PGRs increase stem strength, as well as the better documented effects in terms of reducing crop height. The data below (Table 6.13) showed that PGR application had a detrimental effect on predicted lodging risk, resulting from significant reductions in the stem failure moment compared to the NIL 'control' treatment. Some other experimental data showed slight increases in stem failure moment when using PGRs (though not significant), but overall the effects of PGRs on stem strength parameters have been found to be very inconsistent. Work by Crook (1994) also showed no significant strength increase using PGRs. It is probable that timing and the weather conditions at application need to be favourable for PGRs to cause significant increases in stem strength, and the reduction in plant height seems to be the only really consistent benefit from PGRs.

Table 6.13 The effect of PGR application on stem failure moment and model predicted lodging risk in the MT95 experiment.

Treatment	Stem base failure moment (Nm)	Model predicted *% lodging risk*	
		stem	*root*
NIL	0.065	9	4
5C+T	0.058	15	4

Results (unpublished) from experiments done at ADAS Rosemaund in 1996 also found that PGRs did not significantly affect stem breaking strength compared to an untreated control. The commercial PGRs tested included '5C Cycocel', 'Moddus', 'Cerone' and 'Upgrade'.

6.7.4 *Commercial fungicides*

'Common experience' suggested that through some effect of the fungicidal seed treatment 'Baytan', lodging risk was reduced. When data from 'Baytan' treated plants were entered into the model (Table 6.14), the model also predicted a lower root lodging risk compared to untreated plants. The lower probability (a 3% chance of lodging occurring versus 7% for the untreated crop) was found to be due to 'Baytan' treated plants producing significantly deeper crowns and larger root cone diameters.

Table 6.14 The effect of 'Baytan' seed treatment on crown root anchorage and model predicted lodging risk in 1995.

Treatment	Root cone diameter (mm)	Crown depth (mm)	Model predicted *% lodging risk*	
			stem	*root*
Untreated seed	20.0	18.6	2	5
'Baytan' treated seed	24.1	24.9	2	1

There are also some claims for effects on lodging from the new strobilurin fungicides. The strobilurin 'azoxystrobin' has been observed to keep plants standing upright even under high nitrogen regimes, whereas, plants treated with the strobilurin 'kresoxim-methyl had lodged (Anon., 1997). It was thought that 'azoxystrobin' could be promoting a bigger root plate, making the crop less prone to lodging, although, work had not been done to assess its effect on rooting (Anon., 1997).

Time constraints allowed only initial investigations of the different varieties, plant growth regulators and seed treatments outlined above. A fuller understanding of both the beneficial and/or detrimental effects which these factors may produce, is essential if lodging risk is to be more accurately assessed, than at present.

7. DISCUSSION AND CONCLUSIONS

Firstly, work is discussed which specifically relates to the model findings and subsequent model developments made from this study, and secondly, the main agronomic findings from the experimental work are discussed. Future research is then considered and finally, concluding remarks are made.

7.1 Model development

The following section will consider: a) model developments up to April 1996 with the model version used (7.1.1); then b) developments confirmed as valid by the experimental work (7.1.2) and finally; c) developments clearly needing revision as a result of the experimental work (7.1.3). Attention should also be given to section 7.3.1, which deals with the further continuation of this project in terms of the model development.

7.1.1 *Model developments up to April 1996*

The model described in this thesis was initially developed by Baker (1995) to estimate the wind speed needed to 'uproot' trees. The model has now been much further developed and tested in the work described here, as the foundation for a quantitative assessment method for lodging risk in wheat. The model described requires values for various parameters during the July period, when the wheat crop is most prone to lodging.

Crook (1994) showed from tests done on real and model plants in the laboratory that his theoretical model of anchorage predicted that lodging resistance should increase with the diameter of the root cone, the bending strength of the crown roots and shear strength of the soil. The work done here incorporated the root anchorage model of Crook & Ennos (1993), but undertook a much more 'comprehensive approach' towards the lodging problem by using a whole plant model. Crook & Ennos found important findings relating to root lodging resistance but, Baker (1995) and the author added in and tested many other components such as wind effects, rain effects, built in site characteristics (e.g. field altitude), and integrated all of these to produce a more accurate and realistic 'whole model' (comprising of aerial, stem base and root anchorage components), which was designed around and tested on wheat plants in the field. The complexity of the original root anchorage model has been considerably increased by incorporating a soil wetness expression linked to the shear strength of the soil, and further developments have been achieved in this area since submission of this thesis (section 7.3.1), which have further improved the precision in this area of model work. It is in this area that Graham (1983) concluded that further work should produce the most useful results. This work has also successfully tested the root anchorage model of Crook & Ennos under large scale field conditions which had not been previously done (Fig. 6.8), with results in agreement with the findings of Crook (1994) where lodging resistance increased with larger root cone diameters and greater soil shear strength. Easson *et al.* (1992) achieved useful findings, particularly in relation to the mechanism by which lodging occurred (i.e. that the majority of lodging observed was caused by root failure), and expressed the importance of building a mathematical model to predict high lodging risk situations, which has been achieved in the work described here.

Various aspects of the tested version of the model warrant some further discussion. For example, it should be considered that the average values generated from measurements on the main stems only (used in this model), could differ from values calculated from measurements on all the plant shoots. Work by Berry (*pers. comm.*) has shown that the average stem base failure moment, B_S, (measured from all shoots) is about 20% lower than for the main stem only, and that the weakest tillers are almost 50% weaker than the main stem. These findings suggest that B_S was slightly over-estimated in the model. If the model included all shoots (not just the main stem) the aerial base bending moment, B, would probably decrease slightly (due to the tillers being smaller and weaker) as well as B_S, therefore, this is not likely to have affected lodging risk to any large extent.

When considering any conclusions drawn from the overall model results, it should be recognised that parts of the model are still under development and inputs such as soil parameters, predicted plant parameters for July and soil moisture probability distribution are still required in order to fully develop the model, see steps 4, 5, 7 and 11 in section 6.2. These incomplete sections are therefore likely to have significantly affected the model outcomes because the below-ground section was not fully developed within the version of the model used here. Since results from the MT96 experiment have indicated that root failure was the predominant cause of lodging, whereas the tested version of the model predicted stem failure, proper development of this part of the model is essential. This is the main reason why further analysis of the predicted model results could not be made in Chapter 6.

In summary, the work described here has enabled the model, for any given set of meteorological conditions, to calculate the force imposed by the aerial part of the plant, and compare this with the strength of the stem base and root anchorage, and thereby determine whether lodging will occur. The research done here has fulfilled the initial role of the overall project, by establishing the model and its important lodging risk model parameters, which could then be tested in the field experiments, using the version of the model described in Chapter 3. Finally, it is also clear that the model used here is different (being both more comprehensive and quantitative) to other modelling work previously done (Finnigan & Mulhearn, 1978; Ennos, 1991) or attempted by other workers (Easson *et al.*, 1992). Given further development and validation in the future, it clearly represents the best approach to date in providing the basis for a 'practical' lodging risk assessment scheme for UK wheat growers.

7.1.2 *Developments confirmed as valid by the experimental work*

The method for assessing lodging probabilities described has proved to be reasonably robust at this stage of its development, given that the experimental treatments with high predicted lodging probabilities were similar to the treatments which actually lodged in the 1995-96 season. The model also predicted the most risk for the early sown, high seed rate, high residual nitrogen and nil lodging control treatment, which lodged the most in the field experiments in both 1995 and 1996, indicating a good correlation between predicted and actual lodging.

The development of the lodging model by Baker (1995) and field experimental work described here enabled various plant lodging risk 'indicators' to be investigated and a sensitivity analysis performed. Wind speed and field altitude were found to be much less influential than rainfall in increasing lodging risk (Fig. 6.1). For the canopy, shoot number per plant and centre of gravity height were less influential than plant natural frequency (Fig. 6.2). For the stem base, stem failure stress and stem radius were both influential while stem wall width was less important (Fig. 6.3). Finally, for root and soil factors, the root cone diameter was the most influential factor, although soil strength was also important (Fig. 6.4). The following most important conclusions can be drawn from the work described:

- Both stem lodging and root lodging definitely occur and both types of lodging were observed in the field during the course of the experimental work;
- Plant height alone was less effective as an indicator of lodging risk than the more composite measurement of plant natural frequency (encompassing height and weight of the canopy, including the ear), which was found to be the most effective indicator of lodging risk for the plant canopy;
- For the stem base, stem diameter was the most effective indicator of lodging risk;
- The weight and length of the lower internodes were poor indicators of stem lodging risk;
- The root cone diameter, structural rooting depth and soil strength were the most effective 'indicators' of the risk of root lodging;
- The angle of spread of crown roots and below-ground plant biomass were poor 'indicators' of root lodging risk, and subject to large variability in measurement;
- Soil condition, in particular soil moisture and associated soil shear strength in the top 5 cm of soil are important factors affecting the type of lodging which occurs;
    - high soil moisture (high rainfall)/low soil strength favours root lodging;
    - low soil moisture (low rainfall)/high soil strength favours stem lodging.

7.1.3 *Developments which require model revision*

The following section of discussion focuses mainly on the field studies using the torquemeter in 1996.

More work is needed to further refine the below-ground model but, significant progress has already been made during the course of this work, particularly in relation to the constant k_6, used in the below-ground equation (3.6, Chapter 3). A number of fixed constants (including k_6) were used in the version of the model described here, and a theoretical value for k_6 of 3.53 was used, based on the work of Ennos (1991). However, results from field measurements at ADAS Rosemaund using a hand-held torquemeter (lodging device) designed by Crook & Ennos (University of Manchester) found that the value of the constant k_6 was much lower (0.43). This key finding has enabled the root/soil model to be modified, to better suit conditions found in the field, so that given the root cone diameter and soil shear strength, the resistance to uprooting can be accurately calculated. This represents a significant step in successfully developing the overall model.

The large difference between the original value (3.53) and the new value (0.43) can be explained by a number of reasons. Firstly, different methods were used to measure the root cone diameter (an important component which helps to derive the constant). Ennos (1991) and Crook & Ennos (1993) carefully excavated the whole root-soil cone from soil cores and measured the cone intact (with soil) in the laboratory, whereas the author sampled many plants from the field, washed them thoroughly and then measured the root cone diameter directly from the structural crown roots (section 4.2.5). Although very precise, the method of Ennos was only suitable for a relatively small number of plant samples to be tested in the laboratory, whereas, the method used here was both practical and precise and much more applicable for larger numbers of samples tested from the field. Another reason for the large differences found could be that the Ennos value was a theoretical value based on tests on an overturning plastic disc. It is likely that this did not represent root lodging as well as the natural process that occurs in the field. The work here also benefited greatly from being able to measure the overturning force directly in the field through use of the torquemeter designed by Crook & Ennos, enabling the constant to be redefined to be valid in the field situation. This difference increases the predicted risk of root failure, and in order to be balanced, requires dry soil shear strength values to increase to more realistic values. It was found from field measurements that the value of 15 kPa used in the model for dry soil strength (based on work by Ennos, 1991) was unrealistic. Results showed that for the natural soil type at ADAS Rosemaund, higher values of between 40-80 kPa were much more realistic. Under actual lodging conditions, rainfall reduced soil strengths from around 80 kPa to about 20 kPa, causing lodging by root failure. Both these findings probably explain why the model risk data presented in Chapter 6 are more biased towards stem failure than root failure, under field conditions conducive to root lodging. These two findings will also change the sensitivity of the below-ground model, and will help to correctly calibrate and significantly progress this part of the model.

If the new values for k_6 (0.43) and s_o (50 kPa) were substituted into the model program tested here, it is likely that the model predicted lodging probabilities for root lodging would increase by a factor of 7-8, which would therefore have better predicted lodging which occurred in the field. Therefore, the below-ground model used underestimated root lodging risk and, for this reason, a more empirical comparison between actual and predicted risk was made in section 6.4.

The lower constant value was not used in the work described here because of timescale limitations; the torquemeter was not available in the first year, and, although available in the second year, the ground was too hard throughout the summer to enable successful use. Very limited results were obtained on a few treatments as soil had to be wetted artificially (section 4.25) which was both time-consuming and labour intensive. It was only in the final year of this study that field conditions enabled extensive testing of the torquemeter across different experimental treatments. Subsequently, results which indicated that k_6 should be lower were not obtained until late-July 1996. In summary, the expression used by Ennos (1991) is reasonably robust, but the constants used should be different which was a key discovery from this study. It is fully recognised that as part of the on-going programme, the model probabilities described here from the three years of study, will need re-working with the revised values of k_6 and s_o. Importantly, the work done here has also enabled the hand-held torquemeter to be properly 'field tested' and, as a result it was slightly adapted for improved field-use. This has contributed towards scope for wider use of the equipment as a technique to measure accurately a plant's root failure moment. This may be a useful future tool for plant breeders to assess root anchorage in new varieties (section 7.1).

It should be noted that it was not possible within this thesis to carry out a comparison of predicted risk versus actual measured lodging in the field. This was due to a number of reasons:

1. The model version available for the thesis was not developed as far as was originally envisaged.
2. There were few significant effects of treatments in 1994 and 1995, and very little lodging occurred.
3. The 1996 experimental year coincided with initial preparation of this thesis, and was not intended as a test year for the author's work.
4. The model version available for the thesis did not have appropriate parameters for the prediction of the root lodging which occurred in 1996.

The new constant and revised soil strength values have since been put into the model programme and have made significant improvements, but the subsequent results are part of the on-going research programme with other researchers involved, and are not presented within this thesis.

7.2 Discussion of agronomic findings

This section of the overall discussion considers the main agronomic findings from the three years of study. By reference to some of the model findings and conclusions in section 7.1, this more clearly exemplifies how the model can be (and has been) used to support and interpret conclusions about husbandry, which are discussed fully below.

With less variation between treatments in the first experimental season (1993-94), the most useful data were collected from the 1994-95 and 1995-96 seasons. With effectively no lodging in the 1994-95 season and lodging occurring across most treatments (to varying extents) in the 1995-96 season, an explanation was sought as to what caused this.

Firstly, results demonstrated that the structure of the plant links the effects of husbandry to lodging, which can be demonstrated by the huge range of differences in the % areas lodged of the different treatments (Figs 5.9-5.16). In any year, husbandry had effects on plant structure in the different treatments, all of which were exposed to the same weather conditions (see results in Chapter 5). This does raise an issue as to the importance of husbandry in causing differential lodging between seasons which had different weather conditions. An analysis of results by using the model calculations (Table 6.4) showed that, for the MT96 experiment, aerial forces from the canopy onto the stem base and roots (for the early sown, high seed rate, high residual N and nil control treatment (1HN1)) were twice as high as in the previous season (MT95). This was despite the same wind speed gusts (8 m/s) during the lodging event period in both seasons, suggesting canopy structure was the most important factor. It is therefore likely that the severe lodging in 1996 was a direct result of the large plant canopies produced in that season. With this in mind, results from Table 6.4 also showed that the model calculated stem failure moment, B_S, (0.086 Nm) was nearly three times weaker than the root failure moment, B_R, (0.229 Nm) which explains why lodging occurred by stem failure in this treatment in 1995. At this point, it is also worth noting that stem base disease also contributed significantly towards weakening the stem and increasing lodging risk (Tables 5.31

and 6.9) in some early sown treatments (more prevalent to disease infection) which lodged (especially 1HN1). However, in the MT96 experiment, B_R (0.089 Nm) was very similar in value to B_S (0.062 Nm), and lodging which resulted in this season (which was both earlier and more severe) was caused by loss of root anchorage. The fact that B_S was still slightly lower is probably due to 'noise', and that it is highly likely that other parts of the system interact with each other to make the plant (in this instance) more conducive to lodging by root failure. In particular, it was notable that lodging in MT95 followed only 2 mm rainfall which did not significantly lower soil strength in the upper 5 cm, which was already extremely high (averaging 90-100 kPa) due to the very dry summer. However, lodging in MT96 followed 7 mm rainfall which wetted the top 5 cm considerably and caused a significant decrease in soil strength down to 20-25 kPa. This indicates the importance of the soil strength/soil moisture relationship in determining the lodging risk and the type of lodging which may occur. Table 6.4 shows that the late sown, low seed rate, low residual N and full PGR control treatment (2LO3) was generally very consistent between different seasons in producing a canopy structure which reduced the aerial force that is transferred onto the plant base, compared to the 1HN1 treatment. Furthermore, this treatment also produced a much stronger stem base and root structure, both of which are evident from the high values of B_S and B_R derived from the model. In both 1995 and 1996, no lodging occurred in this treatment. It is concluded that this was a direct result of the lodging resistance gained from optimising plant structure due to crop husbandry.

All the above findings agree with the views of Clare *et al.* (1996) who stated that the overriding factor which determines whether lodging occurs is the size and structure of the plant itself. These findings also support the comments of Graham (1983) who concluded that, of various methods for minimising the risks of lodging, particular emphasis should be placed on the importance of proficient husbandry. However, although not perhaps the overriding factor, weather conditions are without doubt still very important in the lodging event (Pinthus, 1973; Graham, 1983; Easson *et al.*, 1992), and are likely to strongly influence the type of lodging which occurs in the field. Work described above has shown this, and in this respect supports the observations of other workers (mentioned above). Overall, it can be concluded (though only in a semi-quantitative manner) that various parts of the weather/plant/soil system interact to influence lodging, which agreed with the work of Pinthus (1973), Graham (1983) and Easson *et al.* (1992) and supported the hypothesis of Sylvester-Bradley & Scott (1990). The interaction between rain (influencing surface layer soil moisture), soil and root structure was found to be very important in root lodging events whereas different interactions, such as between stem base structure and stem base disease, were found to be more important in a stem lodging event. For example, under very dry soil conditions in 1995, wind gusts resulted in some lodging due to stem buckling whereas when soil conditions were much wetter in 1996 due to higher rainfall, the same strength wind gusts resulted in quite severe root lodging due to loss of anchorage in the soil. These findings were in agreement with Crook & Ennos (1994) who found that root lodging occurred during grain filling when the ears were heaviest and the soil was wet.

As expected from the literature reviewed in Chapter 2, the early sown, high seed rate, high residual nitrogen and NIL PGR treatment lodged more than any other treatment in MT94 and MT95 (see Tables 5.43 and 5.44). More significantly, in MT96, this treatment lodged more severely than all other treatments and also much earlier than most (Fig. 5.9). Results showed that this treatment had a high centre of gravity height (Table 5.25) and more shoots/m^2 in the spring and early summer (Fig. 5.8c), both of which were found to increase lodging risk. It is worth noting that when the G5 'canopy management' was applied, this reduced lodging by 60% compared to the NIL 'lodging control' treatment. This highlights the importance of optimising canopy structure which can reduce lodging even in the absence of PGRs (HGCA, 1998).

Results from 1995 and 1996 showed that lodging significantly effected both yield and quality in both seasons. In the MT95 experiment, lodging in the high seed rate, high residual nitrogen and NIL PGR treatment caused up to just over a 1 t/ha yield loss compared to all other treatments (Table 5.9), and both TGW and specific weight were significantly reduced (Table 5.10). More extensive lodging occurred in the

MT96 experiment, in particular the early sown, high residual nitrogen and NIL PGR treatment which caused yield losses of up to 1.5 t/ha compared to other treatments (Table 5.13) and lower specific weights (Table 5.14). These yield and quality reductions are consistent with findings from previous work (see Stapper & Fischer, 1990; Easson *et al.*, 1992; 1993). In quantitative terms, the yield losses from the lodged experimental treatments described above would have cost £100-150/ha (based on an average price of £100/t for a milling wheat). It is also worth noting that although PGRs caused yield responses with lodging, in the absence of lodging, no significant yield responses were achieved (Table 5.6) which is consistent with the work of Green (1986). In the MT96 experiment, when yields were averaged across all treatments except for lodging control, the G5 'canopy management' treatment yielded 9.18 t/ha compared to 9.75 t/ha for the NIL control, giving a detrimental effect on yield of approximately 0.5 t/ha. At first sight, performance of G5 appeared disappointing though it should be remembered that it had about 100 kg/ha less N than the other treatments. Also, in particular situations where lodging occurred more severely such as in early sown, high residual N plots (Table 5.13), the G5 treatment actually had a yield benefit over the NIL control of just over 0.3 t/ha (Sylvester-Bradley, 1993). PGR treatments gave between 0.8-1.3 t/ha yield benefit in the same situation.

Many basic decisions made each year by the farmer influence lodging risk in one way or another. The major agronomic factors involved are discussed below.

Work done here has shown that variability between varieties in terms of stem base and rooting structure is high (see Tables 5.34, 5.36 and 5.41). Standing power ratings for varieties are produced from data on the % area of lodged crops in NIAB recommended list trials (Fenwick, 1995), and are not related to actual strength or structural measurements carried out on each variety, such as work done here in Chapter 5 and Table 6.10. Results from a Lodging Survey (HGCA Final Lodging Report, *in press*) showed only a weak relationship between 'straw length' and 'standing power' for the 12 NIAB recommended varieties in 1992, and no relationship between 'standing power' and % area lodged. From the survey, it was further concluded that NIAB standing power ratings did not appear to give an accurate prediction of lodging risk in the field. The ratings do not distinguish whether a particular variety is prone to lodging caused by root or stem failure. This type of information would seem essential if different types of lodging control were to be targeted to suit particular varieties, such as in the approach taken in the work done by Scott *et al.* (1994). For example, weak-stemmed varieties (e.g. Beaver) may require PGR applications to reduce crop height, but varieties with poor root structure would require decisions on lodging control to be made much earlier, in order that seed rate adjustments (Easson *et al.*, 1993), use of Baytan (fuberidazole + triadimenol) seed treatment (Montfort *et al.*, 1996) and rolling to consolidate soil structure (Crook, 1994) can be implemented, in an attempt to prevent root lodging.

Results showed that sowing date effects on lodging risk were apparent, but were not as influential as seed rate effects. It should be noted that sowing date effects were probably restricted by a relatively low number of residual degrees of freedom, and that significant effects were found when time between sowing date intervals was large, such as in the MT96 experiment. Early sown crops had a greater canopy freshweight (see Figs 5.5b-5.8b), a slightly greater number of shoots/m^2, were taller (MT94 and MT96), had weaker stem bases and caused a small increase in lodging risk (see Table 6.5). These findings agree with previous research which found that early-sown crops are more likely to lodge (Fielder, 1988; Kirby *et al.*, 1995). It is likely that the advantages of early sowing in terms of yield potential could still be exploited by counteracting the effect on lodging risk with reduced seed rates. Early drilling also increased lodging risk by causing slightly greater shoot numbers/m^2 (see section 5.1.3), weaker stem bases (see section 5.3) and taller crops in some cases. Although not part of the replicated experiments, observations by the author showed that shallow drilled plants had poor anchorage strength resulting from a low root failure moment when measured with the torquemeter. Seed rate is an important consideration in terms of crop establishment and yield (Easson *et al.*, 1993). Equal consideration should apply for seed rate to be used as an agronomic tool to directly decrease lodging risk. A reduction in seed rate (500 to 250 seeds/m^2) reduced lodging risk by improving crown root structure (25% larger root cone diameter, over

60% higher root resistance and more crown roots) which gave a significantly lower risk of root lodging (see Tables 5.39 and 5.40). These findings caused little or no detrimental effect on yield when establishment and tillering were good, and went further to support the literature relating to seed rate (Klepper *et al.*, 1984; Stapper & Fischer, 1990; and Easson *et al.*, 1992). It is worth mentioning here that the low seed rate also increased the number of shoots per plant which was shown by the model to increase lodging risk (section 6.3). However, the increase in root cone diameter is proportionally greater than the increase in shoot number hence, the significant decrease in lodging risk through lower seed rates. No such improvement in root structure was found from a high residual level of nitrogen (N) or from PGR applications, supporting the observations of Easson *et al.* (1995) but, disagreeing with claims from various manufacturers of PGRs. For the residual N treatments, differences in soil mineral nitrogen were quite small in the first year (MT94) and due to the lack of visual differences between plots and time/labour constraints in that year, it was decided not to monitor the treatment. However, larger differences between residual N treatments were obtained in the MT95 and MT96 experiments (Tables 4.1 and 4.2). In both these years, differences between plant structure were slight but, as expected, the high residual N level tended to slightly increase risk. Although these plant structural differences were not always significantly different (Chapter 5), they did appear to be important in terms of actual lodging which occurred in MT96. High residual N plots tended to lodge more severely than low residual N plots (Figs 5.9-5.15). The model did not always detect these slight increases in risk, which may indicate how sensitive lodging could be to small differences in crop structure . PGRs reduced crop height on average by approximately 10 cm (Tables 5.15-5.17) and also significantly increased plant natural frequency by 20-27% (Table 5.18) which, as found in the model sensitivity analysis, is very important in reducing lodging risk. PGR use also decreased the centre of gravity height on average by 3-5 cm, which again was shown to decrease lodging risk (Tables 5.21, 5.22 & 5.25). Findings that PGR use restricted stem extension were in agreement with the general literature (Chapter 2). However, findings that PGR use did not thicken and strengthen the stem (or roots) were in conflict with work by Woolley (1992) and Milford (1991) but, agreed with the findings of Crook (1994).

Both field and model results showed that use of high seed rates significantly increased the risk of lodging (see Tables 5.39, 5.40 and 6.6), as found by Easson *et al.* (1993). Use of the hand-held torquemeter in the MT95 experiment showed that at the lower seed rate, root tensile strength was significantly greater (Table 5.40), again supporting the work of Easson *et al.* (1995) who used a similar testing device in the laboratory. Future developments could see the need for more accurate predictions of optimum seed rate, which is currently being addressed in new HGCA funded research. Currently, farmers tend to use a seed rate that is higher than optimum for the site to avoid problems if establishment is poor due to bad weather, slugs etc. By taking this approach, farmers are automatically increasing the crop lodging risk, and encouraging the widespread annual use of PGRs (Anon., 1996). It appears that farmers are 'risk-averse' in relation to lodging only after establishment, and rely heavily on PGRs in order to reduce lodging. Root lodging occurred in 1996 across many treatments in the field experiment which had been treated with chlormequat (see section 5.6); height was not sufficiently reduced by PGRs and/or other parts of the plant were still lodging prone, such as root structure. This suggests that the use of chlormequat alone may not be sufficient to prevent lodging under high risk situations. Lodging risk predictions from the model should enable high risk sites to be identified, which may require a full PGR programme, and other situations will arise where predicted lodging risk is very low, allowing a reduction in variable costs by not applying PGRs. In summary, results showed that PGRs alone did not resolve the lodging problem but, they did contribute with other factors to reduce overall lodging risk. It should be noted that although the residual nitrogen treatments caused few significant differences, there was commonly a trend for high residual nitrogen (combined with the standard fertiliser nitrogen applied) to increase lodging risk by slight effects on crop structure, which supports the work of others such as Easson *et al.* (1992) and Crook (1994).

From investigations of PGR use schemes in Chapter 6, only the ADAS Winter Wheat Plant Growth Regulators scheme (ADAS, 1996) currently acknowledges recent research from projects such as this. A new recommendation in the ADAS (1996) scheme recognises that lodging is commonly due to root and soil movement, caused by the wet soil conditions and the 'moment of force' from the crop. Hence, they suggest that a well anchored crop , in a consolidated seedbed is very important. The development of the predictive scheme described in this thesis will provide a new and completely different way of assessing lodging risk, which is both interactive and not 'blind' to the state of the crop as it grows and develops. By assessing crop growth more regularly through the season, and by more carefully considering initial varietal choice, seeding rate, drilling date, soil conditions and nitrogen inputs, it should be possible to make PGR decisions on the basis of the 'state of the crop'. Perhaps more importantly than this, through better understanding of why lodging occurs, more crops should be grown which are less lodging-prone entering the spring and summer period, due to better crop husbandry.

Tests of these schemes (see section 6.7.2) showed that despite attempting to minimise lodging risk in a number of experimental treatments (based on the knowledge known at the start of the 'Lodging Project'), the PGR-use schemes still advocated heavy use of PGRs. Results from the MT95 and MT96 experiments showed that the late sown, low seed rate, low residual N treatment had a very low risk of lodging (see section 5.6), yet full PGR programmes were still advocated by the schemes. The PGR use schemes seem to have only limited value. Although they are useful in identifying very high risk crops (which would benefit from full PGR programmes), they also seem to advocate high PGR usage under much lower risk situations. Furthermore, the benefits of PGRs are limited to affecting stem length and not structural root anchorage, which as found in both field results and model results was fundamental to the root lodging which occurred in 1996. Reference to Table 6.11 shows in more detail the problems associated with the PGR schemes. For example, the last two treatments (without PGRs applied) averaged only 10% lodging at harvest in 1996 but, both these treatments were identified by the BASF scheme to require a full PGR programme. Based on 2.5l 5C chlormequat and 1.5l Terpal this could cost growers up to £30/ha (ADAS, 1996). Based on the final lodging scores this cost and use was clearly not necessary. In fact for both these treatments (late sown, low seed rate and low or high residual N), lodging scores were basically reduced to zero (0-3%) at harvest by either a single PGR application at GS 31 or use of 'canopy management' (G5). So, by careful management of the crop canopy for both of these treatments, lodging was prevented without incurring any costs of PGRs. Furthermore, the next three treatments in Table 6.11 averaged approximately 50% lodging at harvest with no PGRs applied. Again the PGR use schemes recommended full PGR programmes to be applied to these treatments; however, examination of final lodging scores (Chapter 5) once again showed that either a single PGR application or 'canopy management' (G5) reduced lodging substantially, to between 3-12%. This is likely to be an acceptable level of lodging or 'risk', bearing in mind that late PGRs such as Terpal are very expensive, up to £26/ha at full rate (ADAS, 1996). The next treatment in Table 6.11 lodged 75% by harvest with no PGR but a single PGR and G5 treatment reduced lodging to 36% and 17% respectively. In this case, a combination of a single, early PGR application and 'canopy management' would probably also have reduced lodging to acceptable levels. Therefore, it can be argued that only one (out of the eight recommended!) 'high risk' treatment (early sown, high seed rate and high residual N), which lodged severely (93%) warranted the full PGR programme as advised by the BASF PGR use scheme. It is also possible to identify specific flaws in the PGR-use schemes. For example, the schemes broadly speaking, give the same weighting for factors such as potential market and site lodging history as they do for seed rate differences (represented by spring plant populations). This is clearly wrong as the results show (section 6.5) that seed rate is the most important factor in determining lodging risk, so should therefore have a much greater weighting than the other factors mentioned.

In summary, the star-ratings and similar schemes are:

a. arbitary and subjective; there is no basis for comparing (say) variety standing power with N effects or seed rate;
b. incomplete; they do not deal with seasonal differences in crop growth and development, roots or soil (as described in this work);
c. empirical, not mechanistic; so they cannot accommodate new developments which may affect crop structure in terms of lodging risk e.g. strobilurin fungicides;

Whereas the model is:

a. quantitative and integral; it allows all effects to be integrated through risk (%) and then the grower should (eventually) be able to calculate the effect of a PGR (or other treatment) will have on risk, and choose the level of risk he/she is willing to accept;
b. comprehensive;
c. mechanistic; allowing explanation and prediction.

The effects of stem base disease were observed in the 1994-95 season, where both sharp eyespot and fusarium foot-rot were prevalent in some areas of the field experiment. Where stems were severely infected by stem base disease, stem failure moment was reduced considerably (see Tables 5.31 and 5.32), resulting in significantly greater (30-40%) predicted lodging risks (Table 6.9). Where possible, preventing or reducing serious attacks of stem base disease should be a priority in terms of stem lodging control, which supports evidence from the literature (ADAS, 1985; Griffin & King, 1985; Jones, 1994).

Findings from the VT95 experiment show that some significant progress has been made by plant breeders over the last 10-20 years in terms of reducing lodging risk through better canopy structure. For example, a comparison between varieties showed that the modern variety Hereward had a larger ear, lower centre of gravity height and higher natural frequency than the older variety Little Joss (Table 5.20). Stem basal structure has also been improved, with Hereward having a greater stem failure moment, a thicker stem wall width and a wider stem diameter than Little Joss (Tables 5.34 & 5.36). Genetic improvements such as the Rht dwarfing genes (Lupton, 1987; Sylvester-Bradley & Scott, 1990) have also gone a long way in reducing lodging risk in modern varieties through reducing plant height, as discussed in the introduction (section 1.3). To complement some of these canopy/stem structure improvements already made by plant breeders, work done here (section 6.3) would suggest that natural frequency and stem radius (diameter) would be good characters to assess in order to select lodging resistant varieties in the future. In summary, plant breeders (in model terms) have made good progress in reducing the base bending moment, B, and increasing the stem failure moment, B_S, (Table 6.10) producing stiffer stems which are less at risk of stem lodging. Probably the most important area which breeders could look to target for genetic improvement against lodging in the future, would be root structure. Model calculated results shown in Table 6.10 indicate that there is more varietal variation in root structure (represented by the root failure moment, B_R) than in either stem base or canopy structure. For example, the model showed Hereward to have a very high B_R (3.88 Nm) as a result of a high number of crown roots and a large root cone diameter, whereas, Cadenza (another modern variety) had a very low B_R (0.86 Nm). Varieties which had a high number of structural crown roots were found to have better resistance to lodging, and breeding of varieties with a higher tiller production would be one way to initiate a greater number of crown roots (as found by Klepper *et al.*, 1984). To conclude this section, there is therefore good scope to further improve varietal resistance against lodging if more focus is put on improving root structure in future varieties.

The main conclusions which were found for the agronomic factors being investigated were as follows:

- NIAB standing power ratings of varieties give a reasonable indication of overall lodging risk, but do not indicate whether strengths or weaknesses are related to stem or root characteristics, or both (see section 6.7.1);
- Use of Baytan (fuberidazole + triadimenol) seed treatment reduced root lodging risk (by over 50%), by causing significantly (both) deeper root crown anchorage (by 34%) and a larger root cone (by 21%), see Tables 5.37 and 6.13;
- Early sowing increased lodging risk in the 1993-94 and 1995-96 seasons (as expected) due to higher centre of gravity, lower natural frequency, less roots and a smaller root cone (Table 6.5). In 1994-95, this pattern of growth was not so apparent;
- Low seed rate reduced lodging risk (both root and stem) in all experimental years (Table 6.6), mainly by significantly increasing root cone diameter (by 15-28%),

crown root number (by 28%) and stem diameter (by 6-9%), and was a major effect as found by Easson *et al.* (1993);

- High soil residual N levels caused slight differences in plant structure which generally did not translate into increased lodging risk (Table 6.7) but, did appear to effect lodging, indicating the variability associated with this treatment;
- 'New 5C Cycocel' (chlormequat + choline chloride) alone and in combination with 'Terpal' (2-chloroethylphoshonic acid + mepiquat chloride) reduced stem lodging risk compared to the NIL 'control' in all experimental years (Table 6.8);
- Although PGRs reduced lodging risk, only the full PGR programme (2.5 l/ha 5C Cycocel at GS 31 and 1.5 l/ha Terpal at GS 45) in combination with 'low risk' husbandry prevented lodging in summer 1996 (see section 5.6);
- The reduced nitrogen 'canopy management' treatment generally reduced lodging risk compared to the NIL 'control', though not as much or as consistently as PGRs;
- PGRs reduced lodging risk through a reduction in plant height (7-22%) and ***not*** by increasing basal stem strength or root tensile strength (see sections 5.3.1-5.3.2);
- The full PGR programme (applications at GS31 and GS45) was more effective than the single programme (at GS31) in reducing plant height (Table 5.17);
- Severe attacks of stem base disease reduced the stem failure moment by 32-44% compared to uninfected stems (Table 5.31).

7.2.1 *Improvements for 'lodging avoidance' guidelines*

The following section outlines some suggestions designed to improve decision-making and the guidelines available to farmers for avoiding or minimising lodging risk before drilling. It is important to recognise that the following section must be put into context in terms of the fact that the advice recommended has come from limited results and knowledge built up over three seasons (1993-1996), at one site and with the treatments described in section 4.1.4. For example, the research done did not examine the full range of sowing dates and seed rates which can be used by growers in the UK, and did not test all the PGRs available, and was not able to test certain other factors such as cultivation techniques e.g. rolling. However, with that said, the work done has produced an extremely comprehensive data set which should give a good overall indication of the important areas for consideration in terms of lodging guidelines, which are well representative of the UK wheat industry as a whole.

It is important to recognise that if growers can be as careful as possible in terms of deciding their 'strategy' at the onset before drilling, then the benefits of this strategy may prevent all or some of the 'tactics' having to be used later in the season when 'damage limitation' may be the only option rather than 'prevention'.

The important decisions for 'strategy' and 'tactics' in lodging control are as follows: 'Strategy' (variety choice, seed treatment, sowing date, seed rate, drilling depth) and 'Tactics' (spring nitrogen, spring rolling, early PGR, late PGR).

'Strategy'

For choice of variety, guidelines presently rely on farmers choosing a variety with a high standing power rating to alleviate lodging risk. Future improvements to NIAB variety listings should adopt more detailed structural shoot and root ratings for varieties, which would enable farmers to differentiate between varieties with high stem failure strength and/or good structural root anchorage, and small base bending moments.

If farmers choose to sow early in early to mid-September, it may be advisable to consider avoiding high seed rates (>375 seeds/m^2) to avoid producing overlarge, lodging-prone canopies in the summer and reduce lodging risk. Slightly later sowing dates (late September to early October) would be a good balance between reducing lodging risk without too much effect on potential yield gain from early sowing.

Wherever possible, seed rates should be adjusted according to the expected crop establishment. If good seedbeds have been produced on moisture retentive soils, and on sites where establishment is historically good, seed rates should be lowered. Results showed that lowering seed rate (from 500 to 250 seeds/m^2) did not have a detrimental effect on yield. This supports previous work on seed rates by Easson *et al.* (1993) where a seed rate of 200 seeds/m^2 (for two varieties; Apollo and Hornet) resulted in only slight lodging (<10%) whereas a seed rate of 400 seeds/m^2 caused 70-90% lodging for the same two varieties. Therefore, from a lodging risk aspect alone, an optimal seed rate would be between 200-300 seeds/m^2 to avoid lodging. Equivalent yields were produced by encouraging tillers and maintaining tiller survival, to produce lower plant populations, which had stronger stem bases and better anchored structural root systems. Using optimal seed rates, target shoot number at stem extension (GS 31) is about 1000 shoots/m^2 (HGCA, 1997b). Luxuriant stands of about 1500 shoots/m^2 were found to have poor root anchorage and were more lodging prone.

Farmers should ensure that seeds are not drilled too shallow (not less than 20 mm), especially in weak strength soils. Field observations and results have shown that plants anchored near the surface are more prone to root lodging than deeper anchored plants. 'Baytan' seed treatment is advisable to improve root anchorage, especially where plants are deep drilled, where Baytan can reduce the extension of the sub-crown internode therefore increasing crown depth and speeding up structural crown root formations (Montfort *et al.*, 1996). This could be useful in situations with early drilling dates, high seed rates (375 seeds/m^2 or more) or weak strength soils e.g. sands, sandy loams etc. or high organic matter soils e.g. fen peats.

'Tactics'

With early sown crops or particularly high seed rates, reducing or delaying spring N applications reduced lodging risk by reducing crop height and by producing a more optimal crop canopy. Perhaps unexpectedly, findings here showed that sowing date had only small effects on shoot number per plant over the three years of study, hence N management was not as effective at reducing lodging risk in this situation.

Spring rolling may also be beneficial with early sown or particularly forward crops, which will help to strengthen the stem base and to consolidate the soil to improve overall plant anchorage, as found by Crook (1994).

If stem basal structure and root structure are poor in early spring (perhaps due to a high seed rate resulting in few shoots per plant), growers could consider using an early application of chlormequat PGR (at tillering) in order to increase tiller numbers, which has been found to strengthen the stem base and produce more structural crown roots.

Finally, if canopies are still large and tall in late spring (perhaps due to being early sown), then PGR application at early or at early and late stem extension may be required to reduce crop height, which was found to consistently reduce the aerial force imposed on the plant base during windy conditions.

7.3 Future research

7.3.1 *Continuation of this project*

A substantial quantity of the further modelling research required will be carried out by my project co-worker P.Berry, some of which is discussed below:

With the important lodging risk parameters identified in this thesis, the next stage of research will involve predicting the actual values of the important mature crop parameters, from simple measurements in the spring. This research is already underway and will form part of another thesis by Berry (unpublished) entitled; 'Predicting lodging in winter wheat'. There has already been some success in predicting model parameters from spring measurements, especially the important root measurements. Once accurate and comprehensive spring predictors have been identified, it is envisaged that their relationships with the mature crop characters will be built into the risk model. This will then enable a prediction of lodging risk to be achieved in the spring, from model input data collected from a small number of simple plant measurements in the spring.

Soil strength is an important part of the lodging model, but is incorporated in a fairly simplistic way in the version described here. Work has shown that soil strength is subject to a large amount of variability (affected mainly by soil type, soil moisture and soil structure/compaction), and it is important that some of this variability can be quantified in order to develop further the root-soil model. Since the completion of this work, we have continued to make progress in describing the influence of soil strength in the model (described below). Whereas the model used two different soil moisture states (wet or dry) to calculate soil strength, more recent developments enable the model to calculate soil strength based on a function of the soil moisture content at field capacity, the soil clay content and a visual score of soil structure (Baker, *pers. comm.*). Expressions for these effects on soil strength are currently being developed using field data from ADAS Rosemaund, the ADAS Visual Structure Score (ADAS, 1982) and work by Guerif (1994). When incorporated into the model, these expressions should enable a more accurate method of accounting for the influence of soil strength on lodging risk.

More details of the on-going work can be found in the final report for the HGCA 'Lodging Project' (Scott *et al.*, 1998) and in the thesis by Berry: 'Predicting lodging in winter wheat' when completed.

7.3.2 *Other future research requirements*

There are a number of other areas following on from this project where further work would be of interest. The developments discussed below are not necessarily derived from results here but, would eventually help to improve the model.

An improvement which could be made in the future is in the area of predicted 'risk'. It would be useful to the farmer if the model could predict a 'risk' for the total lodging period (early June to harvest) to give a 'season estimate', instead of just for one day as was the case described here. This would require measurements to be made both pre and post the main risk period (mid-July) in order to use the model to predict probabilities through the season. Results from the version of the model used here are taken from measurements in mid-July (the peak lodging risk period) although it is clear that lodging can take place as early as late May/early June and continue right up until harvest. This clearly supports the need for a 'seasonal estimate'.

It would be useful to carry out wide-scale development work at a number of sites across the UK to fully validate the lodging risk model. This work could be carried out by groups such as the Association of Independent Crop Consultants (AICC), and would provide a good test of the model in commercial farming situations.

To fully integrate the model in modern UK agriculture, it would be appropriate in the future to make the model 'DESSAC-compliant'. By incorporating the model into the LINK-funded project on Decision Support Systems for Arable Crops (Audsley *et al.*, 1997), the knowledge gained from this research could be used by farmers and consultants in a very practical and applied way.

An analysis of the 'tramline effect' and lodging on field margins would be beneficial to the UK agricultural industry by identifying factors that have widespread and consistent effects. Crops often remain standing beside tramline wheel-ways when other areas of the field have all lodged. It is also common to see lodging along the margins between the field headland and the central parts of the field. Evidence for this was shown by an Aerial Photography Survey (outlined in the HGCA Final Lodging Report (Scott *et al.*, 1998)), which was carried out in July 1992, and included 340 fields covering 2865 ha. The results showed that 92% of the lodged fields contained lodging in the field margin and 97% of the lodged fields contained no lodging in the field tramlines. In the past, many explanations for this type of lodging or the 'tramline effect' have been put forward, For the 'tramline effect', factors such as increased soil compaction around tramlines, crop abrasion, 'wind tunnelling' effects, less competition for light and nutrients, and uneven fertiliser spread behind the wheels, have all been argued as causes. For lodging in headland margins, high plant densities and over-fertilisation due to overlapping during drilling and spreading respectively are generally thought to be the cause. Findings from this work would suggest that a doubling of seed rate for example, in overlapping drill margins would be more important for lodging than a doubling of N in these areas, as plants would be very lodging prone due to both poor root anchorage and weak stem bases.

Soil compaction is often associated with the 'tramline effect', and studies to investigate the effect of rolling to consolidate the soil would be particularly beneficial to help further understand the influence of soil structure on lodging. A limited study of this type has been carried out previously by Crook (1994).

The research described here has already highlighted the major influence of seed rate in influencing lodging risk. A more detailed experimental investigation of seed rate (using a number of differential rates) could produce useful findings in relation to lodging risk. This type of examination of seeding rates targeted to reduce lodging could also provide a useful cost/benefit analysis in terms of information on reducing the unit cost of production in relation to seed rate and lodging. Further developments in this area could see the use of GPS (global positioning system) technology to map spatially variable seed rates in relation to soil type etc.
Another very important area of research which needs to be expanded is in varietal tolerance or susceptibility to lodging, and in particular identifying specific varietal traits which may help to alleviate the risk of lodging. This provides an exciting challenge for plant breeders.

Finally, future research should be considered whereby the same basic principles set out in this work are used to investigate lodging risk in other important cereal crops in the UK such as barley and oats.

7.4 Concluding remarks

The work described here has implications for agronomy, practical agriculture, research and modelling. It has confirmed and consolidated some previous research findings, but most importantly has pulled together all this knowledge and produced the basis to achieve the first composite method to predict and assess lodging risk.

The significance of the work in confirming that both stem and root lodging do occur should not be overlooked. The popular perception of lodging, by most farmers and some workers (e.g. Neenan & Spencer-Smith, 1975), is that lodging results from stem buckling. However, others (Graham, 1983; Easson *et al.*, 1992; Crook &

Ennos, 1993) have concluded that lodging is predominantly due to loss of anchorage in the root/soil system. It is vital that farmers, the agricultural industry and plant breeders recognise the importance of both types of lodging. An awareness of this will ensure that breeding programmes can be targeted at improving root structure as well as stem structure, and that farmers use cultivations and crop husbandry to improve soil management, root structure and canopy size, rather than relying solely on PGRs to prevent lodging. Perhaps most importantly of all, the work done has shown how differences in crop husbandry can hugely effect plant structure to the extent that plants are either extremely conducive to lodging or are very unlikely to lodge; all depending on the 'state of the plant'. If one agronomic message is taken away from the work done it should be to "lower seed rates" whenever possible, which were not found to be detrimental to yield when crops were well managed and, helped to produce plants which had stronger stem bases and better rooting structure, which decreased the risk of both stem and root lodging considerably.

The work has already started to broaden understanding and increase awareness of the causes of severe lodging in the UK. Articles in the farming press (e.g. Crops, Farmers Weekly), demonstrations at major farming events (HGCA Roadshows, ADAS Rosemaund Open Day 95', 96', 97', Arable Farming Event 96', Cereals 97') and presentations made to ADAS Field Consultants, and members of the Association of Independent Crop Consultants and the British Society of Plant Breeders, have all highlighted the research findings described in this thesis. In general, these have emphasised the importance of root failure as a major cause of severe, widespread lodging in the UK.

The identification of lodging risk 'indicators' (outlined on page 149) has guided concurrent research by Berry within this continuing project. The complete prediction scheme for farmers relies on a wider research programme, for assessing early season lodging risk. This will enable decision-making on lodging control to be based on an assessment of the crop's performance in spring of a particular year (Clare *et al.*, 1996), rather than a preordained view of risk, giving a prophylactic, 'risk-averse' approach such as is often used at present. The main emphasis of the follow-on work done after this study will involve accurately predicting the likely values of the lodging risk 'indicators' in July, from simple field measurements made much earlier in the season. If the condition of the mature plant in July can be predicted accurately, the scheme will offer huge potential, in terms of lodging control strategy, understanding and flexibility for the grower. Results to date (Berry, *pers. comm.*) have shown that most of the lodging risk 'indicators' can be successfully predicted by early season measurements; work is continuing.

In conclusion, the use of new technologies together with rapid improvements in crop management combined with 'decision support systems' are required, in order for future wheat production in the UK to remain profitable. The main objective of this research was to improve crop management according to lodging risk, by an awareness of crop growth. This objective has largely been met; development of a quantitative lodging risk scheme is now well underway.

Understanding of a crop's early season lodging risk according to the particular site and season is fundamental to the successful exploitation of the emerging 'precision farming' technology. One aspect of precision farming which may benefit farmers directly by reducing lodging risk, is the use of a Differential Global Positioning System to produce within-field soil maps. These maps may show the variability of soil strength and soil moisture across the field (Blackmore, 1996), and offer the farmer an opportunity to alleviate risk either by using different soil cultivation techniques to improve the soil, or by using lower seed rates in areas of weak soil strength.

Eventually, a quantitative assessment of lodging risk could become part of a decision support scheme such as 'DESSAC' (Audsley *et al.*, 1997) for the winter wheat crop. The outcome of this research, by improving the understanding of the critical components which determine lodging, and by improving the assessment of risk, should lead to more accurate targeting of lodging control, through awareness of the growing crop. This should ultimately lead to a reduction in the unit cost of production for winter wheat growers.

A more in-depth awareness of the characteristics of a crop which give it a tendency to lodge will not only benefit farmers, but will also provide useful information for inclusion in future plant breeding programmes to improve resistance to lodging further.

7.4.1 *Implications for 'technology transfer' to the cereal industry*

An immediate benefit of interest to the grower would be an advisory leaflet on lodging risk, such as the HGCA topic sheets for farmers.

It is envisaged that the lodging risk prediction scheme could be made available to farmers in the form of a PC-based model. Long-term meteorological weather and soils data could be built into the model for specific regions of the country. The assessment of lodging risk would involve a number of simple plant measurements, taken from early spring onwards. Results from these assessments could be entered into the model, which would then produce a lodging risk prediction for the site. It might be possible to run a number of predictions for an individual site, as the crop grows through the spring period. This should enable the identification of high and low risk crops at an early enough stage so that husbandry decisions could be adjusted to control lodging according to risk.

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APPENDIX 1

: Colour Plates

1.1 Extensive field lodging in Herefordshire 1995.
1.2 Large, dense rain-trapping canopy in mid-June.
1.3 Poor management induced mid-stem buckling.

4.2.1 Structural crown root system.
4.2.2 Portable field lodging device (Crook & Ennos, Manchester University).
4.2.3 Video camcorder set up in the MT95 experiment.
4.2.4 Portable Delta-T meteorological station in the MT94 experiment.

5.1 Plot 'stem lodging' in the MT95 experiment.
5.2 Close-up stem failure; buckling of lower internodes.
5.3 Plot 'root lodging' in the MT96 experiment.
5.4 Close-up root failure; loss of anchorage in wet soil.

Plate 1.1 Extensive field lodging in Herefordshire 1995.

Plate 1.2 Large, dense rain-trapping canopy in mid-June.

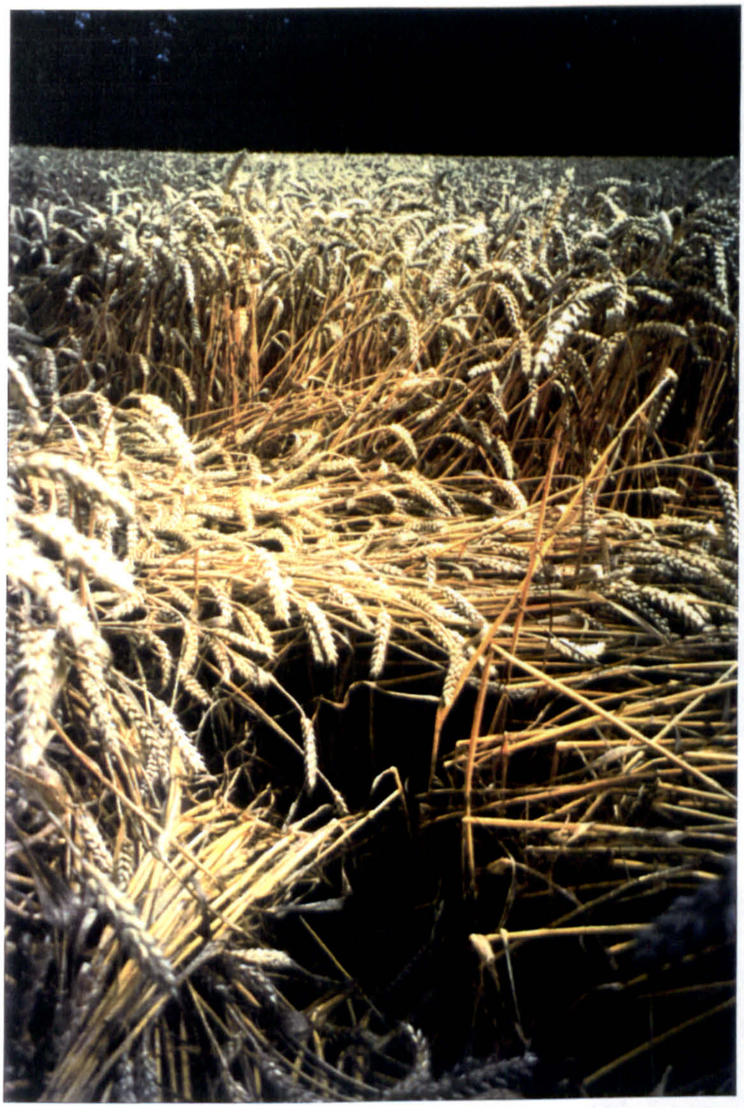

Plate 1.3 Poor management induced mid-stem buckling.

Plate 4.2.1 Structural crown root system.

Plate 4.2.2 Portable field lodging device (Crook & Ennos, Manchester University).

Plate 4.2.3 Video camcorder set up in the MT95 experiment.

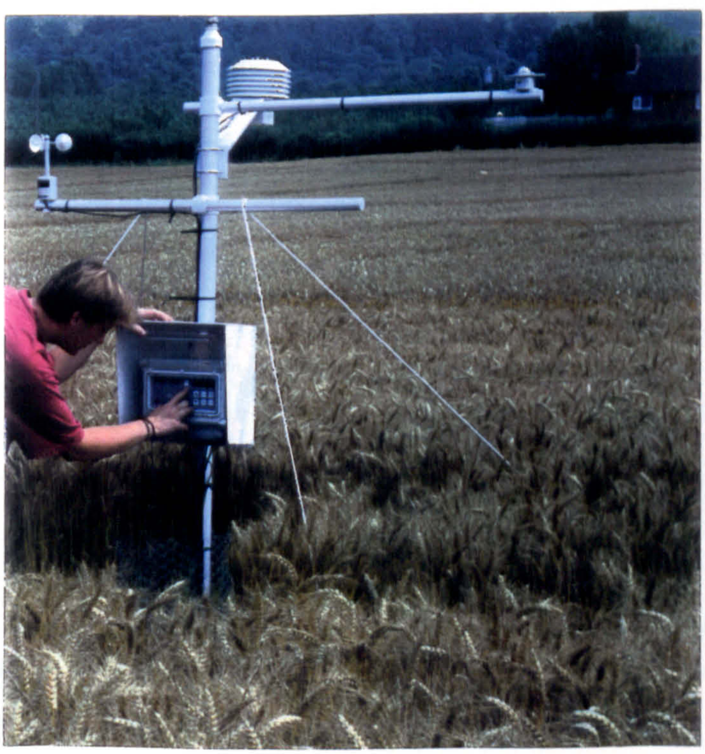

Plate 4.2.4 Portable Delta-T meteorological station in the MT94 experiment.

Plate 5.1 Plot 'stem lodging' in the MT95 experiment.

Plate 5.2 Close-up stem failure; buckling of lower internodes.

Plate 5.3 Plot 'root lodging' in the MT96 experiment.

Plate 5.4 Close-up root failure; loss of anchorage in wet soil.

APPENDIX 2

: Major sampling dates for the experiments

Growth stage	TOS	MT94	ST94	MT95	MT96
30	1	11-Apr	23-26-Mar	23-Feb	18-Mar
	2	20-Apr	13-Apr	03-Apr	22-Apr
31	1	02-May	14-Apr	22-Mar	02-Apr
	2	10-May	26-Apr	10-Apr	29-Apr
39	1	20-May	18-May	12-May	24-May
	2	30-May	27-May	18-May	31-May
59	1	-	-	05-Jun	11-Jun
	2	-	-	05-Jun	14-Jun
69	1	-	-	26-Jun	28-Jun
	2	-	-	26-Jun	29-Jun
72	1	08-Jul	04-Jul	03-Jul	01-Jul
	2	13-14-Jul	05-Jul	03-Jul	02-Jul
87	1	05-Aug	01-Aug	-	12-Aug
	2	09-Aug	03-Aug	-	14-Aug

: Trial Plans

1) MT94 experiment
2) MT95 experiment
3) MT96 experiment

HGCA LODGING TRIAL
Dormington 1993-1994
Winter Wheat cv. Mercia

DISCARD	H2 O	H2 N	H2 O	H2 N	DISCARD	DISCARD	L1 O	L1 N	L1 N	L1 O	DISCARD
	85	86	87	88			93	94	95	96	
	H2 N	H2 O	H2 N	H2 O			L1 N	L1 O	L1 N	L1 O	
	81	82	83	84			89	90	91	92	

DISCARD	H1 N	H1 N	H1 O	H1 O	DISCARD	DISCARD	L2 O	L2 N	L2 N	L2 N	DISCARD
	69	70	71	72			77	78	79	80	
	H1 O	H1 O	H1 N	H1 N			L2 O	L2 O	L2 O	L2 N	
	65	66	67	68			73	74	75	76	

Time of sowing
1. 16 October 1993
2. 8 November 1993

Seed rate
H. 500 seeds m2
L. 250 seeds m2

Autumn Nitrogen
O. Nil
N. 80kg/ha N

Lodging control methods
A. Nil
B. Chlormequat @ GS 31
C. As B. + Terpal @ GS 45
D. Late Nitrogen

DISCARD	H2 O	H2 N	H2 O	H2 O	DISCARD	DISCARD	H1 N	H1 N	H1 O	H1 O	DISCARD	DISCARD	L1 O	L1 N	L1 N	L1 N	DISCARD	DISCARD	H2 N	H2 O	H2 N	H2 O	DISCARD
	21	22	23	24			29	30	31	32			53	54	55	56			61	62	63	64	
	H2 N	H2 N	H2 O	H2 N			H1 N	H1 O	H1 N	H1 O			L1 N	L1 O	L1 O	L1 O			H2 O	H2 N	H2 O	H2 N	
	17	18	19	20			25	26	27	28			49	50	51	52			57	58	59	60	

DISCARD	L1 N	L1 N	L1 O	L1 O	DISCARD	DISCARD	L2 O	L2 O	L2 O	L2 N	DISCARD	DISCARD	L2 O	L2 N	L2 N	L2 O	DISCARD	DISCARD	H1 N	H1 N	H1 O	H1 N	DISCARD
	5	6	7	8			13	14	15	16			37	38	39	40			45	46	47	48	
	L1 N	L1 O	L1 N	L1 O			L2 N	L2 N	L2 O	L2 N			L2 N	L2 O	L2 O	L2 N			H1 O	H1 N	H1 O	H1 O	
	1	2	3	4			9	10	11	12			33	34	35	36			41	42	43	44	

HGCA INTERGRATED LODGING, LINK-N AND DEVELOPMENT TRIAL

BELMONT 1994-1995 WINTER WHEAT CV. MERCIA

PLOT DIMENSIONS : 18m x 4m PLOTS, WITH 12m INTERNAL HEADLANDS

SEED RATE	D I	L	L	L	L	L	L	L	L	D I	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	D I	H	H	H	H	H	H	H	H	D I	L	L	L	L	L	L	L	L	D I
RESIDUAL N	S C	O	N	N	N	O	O	N	O	S C	O	O	N	N	N	N	N	O	N	O	O	O	N	N	N	O	S C	O	O	O	N	O	N	N	N	S C	O	O	N	O	N	O	N	N	S C
TREATMENT	A R	3	1	2	4	2	4	3	1	A R	2	7	7	4	3	3	3	4	6	1	6	3	1	5	2	5	A R	4	1	2	3	3	2	1	4	A R	2	3	1	4	4	1	2	3	A R
PLOT	D	81	82	83	84	85	86	87	88	D	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	D	105	106	107	108	109	110	111	112	D	113	114	115	116	117	118	119	120	D

TOS 1 (81 - 104) TOS 2 (105 - 120)

SEED RATE	D I	L	L	L	L	L	L	L	L	H	H	H	H	H	H	H	H	D I	H	H	H	H	H	H	H	H	H	H	H	H	H	H	D I	H	H	D I	L	L	L	L	L	L	L	L	D I
RESIDUAL N	S C	N	N	N	O	O	O	N	O	O	O	N	N	N	O	N	O	S C	N	N	N	N	O	O	N	O	O	N	O	O	N	O	S C	N	N	S C	N	O	O	N	O	N	O	N	S C
TREATMENT	A R	3	4	2	4	2	1	1	3	1	3	4	3	2	2	1	4	A R	3	3	3	2	1	2	4	7	5	6	3	6	7	4	A R	5	1	A R	2	2	1	1	4	3	3	4	A R
PLOT	D	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	D	57	58	59	60	61	62	63	64	65	66	67	68	69	70	D	71	72	D	73	74	75	76	77	78	79	80	D

TOS 2 (41 - 56) TOS1 (57 -80)

SEED RATE	D I	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	D I	L	L	L	L	L	L	L	L	D I	L	L	L	L	L	L	L	L	D I	H	H	H	H	H	H	H	H	D I
RESIDUAL N	S C	O	O	N	N	O	O	N	O	N	N	N	N	O	N	O	N	S C	N	O	O	O	N	N	O	N	S C	N	O	O	O	O	N	N	N	S C	N	O	N	O	N	N	O	O	S C
TREATMENT	A R	1	5	1	5	7	2	4	3	3	3	3	6	6	7	4	2	A R	1	2	3	4	4	2	1	3	A R	3	1	3	2	4	2	1	4	A R	1	2	3	3	4	2	4	1	A R
PLOT	D	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	D	17	18	19	20	21	22	23	24	D	25	26	27	28	29	30	31	32	D	33	34	35	36	37	38	39	40	D

TOS 1 (1 - 24) TOS 2 (25 - 40)

TREATMENTS :

1. TIME OF SOWING
   T.O.S. 1 = MID-SEPTEMBER
   T.O.S. 2 = MID-OCTOBER

2. SEED RATE
   H. 500 s/m2
   L. 250 s/m2

3. RESIDUAL NITROGEN
   O. NIL
   N. 200 kg

4. LODGING CONTROLS
   1 1 A. NIL
   2 2 B. CHLORMEQUAT @ GS 31
   3 3 C. AS B. + TERPAL @ GS 45
   4 4 D. LATE NITROGEN
   5 5 GAI 5 +
   6 6 GAI 5 −
   7 7 NIL

JUBILEE 95-96 WINTER WHEAT CV. MERCIA

PLOT DIMENSION 24M X 4M

																	D	D	D					I																					
SEED RATE	D I	L	L	L	L	L	L	L	L	D I	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	D I	L	L	L	L	L	L	L	L	D I	H	H	H	H	H	H	H	H	D I
RESIDUAL N	S C	N	O	O	N	N	N	O	O	S C	N	N	O	O	O	N	N	N	N	O	N	N	O	O	N	O	S C	O	N	N	O	O	O	N	N	S C	O	N	O	O	N	N	O	N	S C
TEATMENT	A R	4	2	1	2	3	1	4	3	A R		4	3				3	3	3	4	2			1	1	2	A R	3	1	2	2	1	4	4	3	A R	4	1	2	1	2	4	3	3	A R
PLOT	D	81	82	83	84	85	86	87	88	D	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	D	105	106	107	108	109	110	111	112	D	113	114	115	116	117	118	119	120	D

TOS 1 (81 - 104) TOS 2 (105 - 120)

SEED RATE	D I	H	H	H	H	H	H	H	H	D I	L	L	L	L	L	L	L	L	D I	L	L	L	L	L	L	L	L	D I	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	D I
RESIDUAL N	S C	N	O	O	N	O	N	O	N	S C	O	O	N	O	O	N	N	N	S C	O	N	O	O	N	N	O	N	S C	O	N	O	O	O	N	N	N	N	N	N	N	O	O	N	O	S C
TEATMENT	A R	3	4	2	1	1	2	3	4	A R	2	3	4	1	4	1	2	3	A R	2	2	4	3	3	1	1	4	A R		1	3		2		3	3	3			4	1		2	4	A R
PLOT	D	41	42	43	44	45	46	47	48	D	49	50	51	52	53	54	55	56	D	57	58	59	60	61	62	63	64	D	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	D

TOS 2 (41 - 56) TOS1 (65 - 80)

SEED RATE	D I	L	L	L	L	L	L	L	L	D I	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	D I	L	L	L	L	L	L	L	L	D I	H	H	H	H	H	H	H	H	D I
RESIDUAL N	S C	O	O	O	N	N	O	N	N	S C	N	O	N	O	N	O	N	N	N	O	N	O	O	N	O	N	S C	O	N	N	N	O	N	O	O	S C	O	N	N	O	O	O	N	N	S C
TEATMENT	A R	3	4	2	4	3	1	2	1	A R		3				1	3	3	3		1	2		2	4	4	A R	3	3	2	1	2	4	1	4	A R	3	2	4	2	4	1	3	1	A R
PLOT	D	1	2	3	4	5	6	7	8	D	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	D	25	26	27	28	29	30	31	32	D	33	34	35	36	37	38	39	40	D

TOS 1 (1 - 24) TOS 2 (25 - 40)

L = LINK-N TRIAL PLOTS
D = DEVELOPMENT TRIAL PLOTS

TREATMENTS

1. TIME OF SOWING
   - T.O.S. 1 = MID-SEPTEMBER
   - T.O.S. 2 = MID-OCTOBER
2. SEED RATE
   - H. 500 s/m2
   - L. 250 s/m2
3. RESIDUAL NITROGEN
   - O. NIL
   - N 350 Kg/ha
4. LODGING CONTROLS
   - 1 A. NIL
   - 2 B. CHLORMEQUAT @ GS 31
   - 3 C. AS B. + TERPAL @ GS 45
   - 4 D. LATE NITROGEN

APPENDIX 3

: Lodging Model Equations

The Weibull distribution for wind speed probabilities.

$$p_w = e^{-k_1} V^{k_2} \quad \text{(A.1)}$$

$$0.5 = e^{-k_1} V_{50}{}^{/k_2} \quad \text{(A.2)}$$

$$0.01 = {}^{-k_1} V_{99}{}^{/k_2} \quad \text{(A.3)}$$

$$V_{50} = V_{50}{}' (1n\ (1/z_0) / 1n\ (10/z_0))\ (1 + 0.0007h) \quad \text{(A.4)}$$

$$V_{99} = V_{99}{}' (1n\ (1/z_0) / 1n\ (10/z_0))\ (1 + 0.0009h) \quad \text{(A.5)}$$

The relationship between gust speed and mean wind speed.

$$V_g/V = 1 + (\sigma_v/V)\ L \quad \text{(A.6)}$$

$$L = J_1\ g_v \quad \text{(A.7)}$$

$$g_v = \sqrt{2}\ln\ (J_2nT) + 0.577 / \sqrt{2}\ln\ (J_2nT) \quad \text{(A.8)}$$

$$J_1 = 1 - 0.1925\ (2n\ {}^xL_v / V) + 0.1)^{-0.6792} \quad \text{(A.9)}$$

$$J_2 = (n\ {}^xL_v / V)-1\ (0.0066 + 0.2130\ (2n\ {}^xL_v / V))^{-0.6543} \quad \text{(A.10)}$$

The exponential distribution for rainfall probabilities.

$$p_R = e^{-k_3 i} \quad \text{(A.11}$$

$$0.5 = e^{-k_3 i50} \quad \text{(A.12)}$$