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A STUDY OF LODGING IN CEREALS

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A STUDY OF LODGING IN CEREALS

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Diagram Of Wheat Plant Showing Points Of Weakness, And Probable Modes Of Structural Failure.

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ABSTRACT

Over a three year period field and laboratory experiments and theoretical studies were carried out with a view to establishing the mechanism by which lodging occurs in wheat and of building a mathematical model which could be used to predict high lodging risk situations. Data were gathered on the mechanical properties of wheat stems and on the morphological changes taking place during the period when the crop is most at risk from lodging. The nature of the root system was also studied under a range of conditions, the breaking strain of roots tested and the load required to pull roots free from both dry and wet soils established. The relationship between weather and lodging events was studied using hourly weather data and field observations of lodging and the behaviour of individual stems within a crop stand was investigated using video recording. The magnitude of the forces likely to be occurring in individual roots was modelled using Finite Element Analysis, but extension of this approach to include the stem was not accomplished within the project.

An integrated picture of the lodging process emerged from the project in which the crop, the weather and the soil all play roles in determining the incidence and severity of lodging. The aerial part of the crop generates a force acting on the root/soil system. The ability of this system to provide support, the critical loading, depends largely on the soil wetness and the nature of the root system. Rainfall which wets the soil also adds to the weight of the crop generating the force. The crop characteristics vary continuously during development and maturation so that the loading on the root system also varies. This can be described by a loading response coefficient. Further manipulation of the data from this project is required to determine the critical loading and response coefficients and how agronomic factors, namely nitrogen, sowing date, sowing rate, growth regulator and variety determine the characteristics of the crop and these parameters.

Other features of the crop soil system, namely visco-elastic creep, damping and rhizo-sheath development are discussed but further experimentation is needed to describe the role they play in lodging. Techniques were developed which could be used in further studies of lodging particularly investigations of wind effects on crops and measurement of the forces being generated.

It is proposed that manipulation of the development of the root system and root/soil cohesion through soil cultivation may contribute to enhanced resistance to lodging in crops. Further investigations are needed to explore this hypothesis taking into consideration soil type.

Chapter 1

Introduction

Lodging has for many years been recognised as one of the main limiting factors in cereal production systems. It is a more widespread problem in winter barley and oats than in wheat, but where it does occur in wheat its effects are serious. Lodging of the mature cereal crop, and the associated problems of brackling and necking in barley, can lead to significant harvest losses, higher drying costs and a reduction in grain quality. Earlier lodging of the crop during grain filling is considerably more serious as it also results in reduced grain fill. The risk of lodging is an important consideration limiting nitrogen usage, and many other management decisions, such as choice of variety, seed-rate, sowing date, nitrogen timing, disease control and the use of plant growth regulators, are influenced by the risk of lodging.

Research into reduction of the risk of lodging has been largely empirical. Plant breeders have selected varieties which have shown better standing power and shorter straw and chemical manufacturers have tested for chemicals which inhibit straw elongation or which reduce the incidence of lodging in field experiments. Relatively little effort has been put into coming to a clear understanding of how lodging occurs so that a more scientifically based strategy can be developed for reducing the risk of lodging. The current project was proposed, therefore, with the aims of firstly investigating and establishing how lodging actually happens and secondly of using this information to devise ways of advising farmers as to the potential 'high risk' situations and the best course of action to reduce the risk.

From the start of the project it was clear that lodging is not a simple phenomenon but is the failure of a complex plant/soil support system at its weakest point. By attempting to bring together the physical and biological properties of the components of that system in a 'model' it was intended that the point of failure could be pin pointed and ways of strengthening the system identified.

The project began in the middle of the 1988 cropping year and two further years of field experiments were conducted. In view of the limited opportunity to collect data during the short duration of this project the conclusions drawn are tentative in many cases and subject to modification on the basis of more complete evidence. While the project failed to complete its objective of putting into place a complete 'model' of lodging which would be immediately useful to the farmer, we believe that it has succeeded in challenging the perceived understanding of lodging, gone a considerable way towards creating a useful 'model' and has pointed the way for further work which could be of practical benefit.

Definition of the term 'lodging'

For the purpose of this study lodging is considered to have happened when the plant stems reach a lying position on or close to the ground from which they cannot recover. Although lodging can occur as a result of disease on the stem or roots this source of lodging is not dealt with and only those forms of lodging arising from failure of otherwise healthy stems or roots or from changes in the soil properties are considered in the study.

A brief literature review

Popular knowledge of lodging and its detrimental effects were summarised in Thomas (1982). In a paper presented at an RASE NAC Cereal Unit Course for farmers and consultants he stated that most lodging was the result of stem fracture and therefore emphasis was placed on stem characteristics such as length, weight, rigidity, diameter, wall thickness and material strength. In his discussion of growth regulators, effects on length and rigidity of stems and the consequent benefits for control of lodging were presented.

Scientific knowledge of lodging is recognised by many workers as being based on Pinthus' (1973) masterly review. More recently Graham (1985) pursued an inter-disciplinary approach in attempting to further unravel the mystery that is conveniently shrouded by the word "lodging".

Pinthus (1973) concluded that on a world scale root lodging was the predominant type of lodging occurring in cereals because plant anchorage was reduced when the soil is wetted by rain or irrigation. He commented that in many experiments conducted to establish relationships between individual characteristics and lodging correlations were usually not very high and consistency was lacking. He made no attempt to integrate all these characteristics into a single picture of the whole system. However, he did recognise that interactions occurred and that some characteristics were more responsive to environment and management than others. Neenan and Spenser-Smith (1975), on the other hand, believed that they had demonstrated that lodging in wheat and barley was due to stem breakage and not by loss of anchorage.

In a thorough examination of the phenomenon Graham (1985) asserted that the morphological and anatomical crop and plant characters associated with lodging were not causal. He postulated, in general agreement with Pinthus, that mass failure of the surface soil was the reason for lodging rather than buckling of the stem. However, he did recognise that plant characters influenced lodging and were inter-related.

Pinthus (1973) and Graham (1985) both present comprehensive descriptions of the different types of lodging, their effects on yield, quality and harvestability and the control of lodging through husbandry practices such as plant growth regulator application, judicious use of nitrogen and choice of lodging-resistant cultivars. It is therefore not considered necessary to present an argument justifying work on lodging, its detrimental effects being widely appreciated already.

Thus in approaching the phenomenon of lodging against this background, we were aware that:

(1) There was no consensus as to whether root or stem failure is the cause of lodging, proponents of both views having both circumstantial and experimental evidence.

(2) Many stem and root characteristics had been found by research workers to have some degree of correlation with the incidence of lodging indicating the complex nature of the phenomenon.

(3) Effective measures exist to reduce the risk of lodging but that given the vagaries of the weather in some years these may only ameliorate rather than prevent lodging.

A Description of the Plant/Soil System

The plant and soil system can be thought of in two interacting parts, an aerial shoot system, which undergoes various bending and tensile stresses and which generates a force and moment acting at the stem base, and a root soil system which resists this force and moment. The possible types of failure which could give rise to lodging in cereals need to be considered within the context of this overall system.

The aerial shoot system and likely points of failure

The aerial shoot system is composed of the above ground parts of the plant and the forces acting on them. When the wind acts on the crop, the interaction between the wind and the surface of the plant generates drag. This force, combined with the weight of the plant (and any water lying on it) once displaced from its equilibrium position i.e. the vertical, will create a bending moment. The degree of bending of the stem will depend upon its elastic properties. Energy during the bending of the stem results in an oscillation which is dampened by the interaction of neighbouring plants. The remaining part of the bending moment acts at the point of the system where it is fixed i.e. the stem base in the soil. The drag also creates a force which can be considered as acting horizontally at the fulcrum of the stem at the soil surface.

The aerial shoot system could possibly fail in two ways:

i) By mechanical failure through stem breakage or buckling.

ii) By visco-elastic creep, which is the progressive failure of the structure of the composite material of the stem as a result of repeated bending. The consequence of this would be loss of stem elasticity and rigidity so that it would be unable to maintain an upright position.

Root soil system and likely points of failure

The root soil system is composed of the soil, the root system, those parts of the crown of the plant which are at or below ground level and the reaction forces generated within them. This system provides a reaction to both the turning moment resulting at the base of the plant from the action of the wind and the horizontal force acting at the soil surface. The reaction may be provided by the soil's resistance to compression and shear or by the roots under tension, compression or shear.

Failure of the root soil system, which will result in irreversible lodging, could arise from:

i) Changes in soil properties. The loss of soil strength and the consequent weakening of the support of the soil for the crown and decrease in the cohesion of the soil to the root surface could result in lodging. Such changes could result from wetting of the soil.

ii) Mechanical failure of the roots. The roots or even the crown itself could be subject to mechanical failure. In the region close to the crown the roots are strong, but become progressively weaker in tension further from the crown. The roots, however, cannot be considered separately from the soil. Failure of the root/soil bond has to occur prior to the root itself failing.

Given these possible modes of failure our objectives were:

(1) To define, in mathematical terms where possible, the structural support system for wheat plants and how it fails during lodging.

(2) To evaluate the role of plant and crop characteristics in the process of lodging;

(3) Using this knowledge to identify possible new strategies for the control of lodging.

Chapter 2

Project outline

The project was carried out over the three year period from April 1988 and was based at the Agricultural Research Institute of Northern Ireland, Hillsborough. It was decided that the project should concentrate on lodging in wheat as the consequences of lodging in this crop are more serious than with the other temperate cereals. The work of the project involved both theoretical consideration of the modes of failure based on engineering theory and determination of properties of the plant and soil through experimentation. Knowledge gained through each of these activities influenced the development of both throughout the project.

1988 Season:

* The occurrences of lodging in field and plot areas were observed as closely as possible.

* Morphological and mechanical properties of wheat stems were determined in order to develop a more complete model of stem structure and its role in lodging.

* By the end of the season it was clear that lodging was unlikely to be related stem failure, which had been the original hypothesis, and that other likely areas of failure such as the root system would need to be investigated.

1989 Season:

* A nitrogen/growth regulator field experiment was established to provide a range of plant material for detailed work on plant characteristics and lodging. As a result of the exceptionally dry season no lodging occurred in the plots even when the soil was artificially wetted.

* Further data were collected on the stem properties including internode structure, stem bending and visco-elastic creep.

* Properties of roots and their relationship with the soil were studied in pot experiments.

* The relationship between windspeed and the movement of wheat stems both individually and in a crop stand was examined in order to gather data from which the loading likely to be placed on the root system by the aerial stem system could be derived.

* At the end of this season more was known about the nature and physical properties of both the stem and the root systems, but little progress was made on establishing how it was failing during lodging.

1990 Season:

* Field experiments were established involving different varieties, seed-rates, nitrogen rates and growth regulators.

* Observations were made of extensive lodging which occurred in the seed-rate / variety experiment and correlated with hourly rainfall and wind data.

* Small scale experiments were carried out on the pulling of roots from wet and dry soils.

* Wheat plants were dug up from lodged and unlodged plots at various seed rates and data collected on characteristics of the root and shoot systems.

* The root systems were modelled as engineering structures and the tensions likely to arise in individual roots derived using finite element analysis software.

* An attempt was made to model the stem using the same finite element analysis software.

This was found to be more complex to model than the root system, and due to the inability of the structural engineering package to handle the large scale deflections occurring in wheat this area of the model could not be completed.

In this report the various strands of the project are brought together in the light of literature covering a wide range of disciplines from mechanical engineering to plant biochemistry. Parts of the model for which there is adequate data are put together and the arguments presented to show why stem failure is unlikely to be the main cause of lodging in wheat and why failure of the root/soil interface is more likely. In the body of the report data are presented in summary form, with fuller data sets placed in appendices. Conclusions are drawn regarding how our understanding of lodging can be further progressed and on how the findings of this report could be of help to cereal growers.

Chapter 3

Field observations of lodging

Over the course of this project the observation of various lodging events allowed a study to be made of the types of lodging which occurred and of the relationship between the occurrence of lodging and the pattern of weather at the time. The relationship between weather and lodging has been discussed in the literature (Hough, 1990) but there have been no recorded attempts to study the relationship directly.

1988 Season

While it might be considered common-place to observe that lodging occurs as a result of the action of wind and rain on the crop the initial observations made in 1988 of lodging as it occurred (Appendix 1) revealed a number of important features.

i) Lodging was not a sudden event but tended to take place over a period of hours during which time the crop, constantly moving due to the action of the wind, initially returned to the vertical from each movement and then began to lie at an angle before gradually becoming fully lodged.

ii) Areas of the crop first lodged during a period of high wind on a day when there was no rainfall, although over 11mm had fallen over the previous 2 days (Figure 3.1). Further areas lodged a few days later, also on a day when the wind-run again reached a peak following two days with moderate rainfall. Subsequently more areas lodged during a period when there was moderate rainfall but wind-speed was low.

iii) Similar weather periods occurred again after this but no significant increases in the area lodged were observed.

iv) The area of lodging extended across the full width of high N plots, but adjacent plots which had received lower rates of nitrogen did not lodge. The direction of lodging was predominantly across the plot, but some areas lodged down the plot or at intermediate angles.

v) The soil was 'moist' but not 'wet' and appeared structurally sound. Only five to ten percent of the stems showed physical damage. In a number of cases there was clear evidence of plants pulling away from the soil.

1989 season

During the 1989 growing season rainfall during the latter part of June and most of July was very low resulting a high soil moisture deficit. Rainfall and wind-run were high in the last week of July and the 2nd week of August when over 55mm fell during a 6 day period and although this was greater than that immediately preceding the lodging in 1988 no lodging was observed (Figure 3.2). Towards the time of harvest about 10% lodging was observed in the mature crop at the higher N rate.

1990 Season

Extensive lodging took place in the seed-rate variety experiment and detailed recording of the lodging and weather events was made. In Figures 3.3 and 3.4 the lodging events, meaned over the 4 varieties, are plotted against the hourly data for rainfall, windspeed and wind direction. Graphs of the incidence of lodging in each variety at the six seed-rates are given in Figure 3.5. A full description of the incidence of lodging is given in Appendix 1.

Each lodging event was found to be associated with rainfall in the previous 24 hour or 48 hour period. Association of lodging with strong wind is less clear although in a number of cases strong winds were present either along with the rain or shortly afterwards. There did not appear to be a strong connection with wind direction, although the stronger winds accompanying some lodging events came shortly after a change in wind direction. The direction of lodging was found to be variable, even within plots. As observed in 1988 lodging tended to occur in 'swathes' falling across or along the plot, or at an angle. Several 'swathes' in different directions were often observed in one plot.

On several of the scoring dates the crops were seen to have 'recovered' from lodging. In some cases the weight of water present on the crop resulted in the appearance of lodging, but when the water evaporated or ran off the crop was able to regain an erect or semi-erect position. The amount of water lying on the crop was found to be approximately 1.1kg on one square metre of lying crop, with 880g on the same area of standing crop (Table 3.1). It was more often the case, however, that the observed recovery was in the form of upwards bending of the stems at the 2nd or 3rd nodes. This was noted particularly on 11th June in those plots which had lodged on the 4th June before anthesis, but also at subsequent dates. The stems which recovered in this manner had little stability and very readily lodged again as a result of further wind and rain.

Table 3.1

The surface water lying on standing and lodged areas of wheat after heavy rainfall

Mean of 30 stems, cv Norman, 500 stems per m^2.
Surface water measured by absorption onto dry tissue.

	surface dry stem weight	surface water per stem	surface water per square m
Erect crop	9.09g	1.76g	881g
Lying crop	9.49g	2.18g	1091g

The seed-rate treatments had a direct effect on the occurrence of lodging. The first lodging, observed at the beginning of June before anthesis, occurred in the 1600 seed-rate plots resulting in almost complete lodging of all four varieties. Substantial lodging in the 800 seed-rate plots followed a few days later for the variety Norman but with Hornet it was more than a month later, the other varieties lodging between these dates. Lodging at the 400 and 200 seed-rates then occurred progressively later into July and August, the differences between varieties remaining relatively consistent. With Hornet and Apollo no lodging occurred at the 200 seed-rate and at the lower rates none of the varieties lodged.

Apollo was the tallest of the four varieties but had less lodging than Longbow or Norman. At all seed-rates this variety tended to lean at an angle of between 10^o and 30^o from the vertical. Hornet, which was the most lodging resistant, remained stiff and vertical before lodging more suddenly. In plots where part of the area had lodged the remainder of the plot tended to be left leaning at 30^o to 45^o from the vertical.

Discussion of lodging observations

From the observation that crop areas lodge gradually over a period of hours and the absence of buckled stems it seems unlikely that the mode of failure is stem breakage or buckling. Of the possible modes of failure in the root/soil system loss of anchorage due to failure of the soil alone cannot explain differences in lodging incidences observed between nitrogen and growth regulator and amongst varieties in experiments conducted on uniform soils. This leaves the possibilities that the stem failed through visco-elastic creep, or that the root/soil system failed in a way that is influenced by both the soil and the plant characteristics.

The general weather data which were gathered are not able to provide a precise measure of the forces acting on the crop. For example, the run of wind over a given period does not indicate the intensity of wind gusts over the surface of the crop or their variation in direction. It is not surprising, therefore, that lodging cannot be consistently related to particular patterns of recorded weather. Nevertheless the data indicate that rainfall plays a more important role than wind speed in the occurrence of lodging, and that lodging events can occur up to several hours after the rainfall has taken place. Soil wetness is likely to be an important contributory factor. The substantial weight of water on the surface of a wet crop also has to be taken into account and may continue to exert an influence for several hours after the rainfall has stopped.

It is not possible by simple observation to identify how increasing seed-rate contributed to the increased incidence of lodging. It is most probable that a number of the effects, such as increased total above ground biomass, fewer roots per stem and taller stems 'conspired' together to increase the propensity of the crop to lodge. The data gathered from this experiment will, however, provide a valuable database against which the model of lodging which is being built can be tested.

Figure 3.1

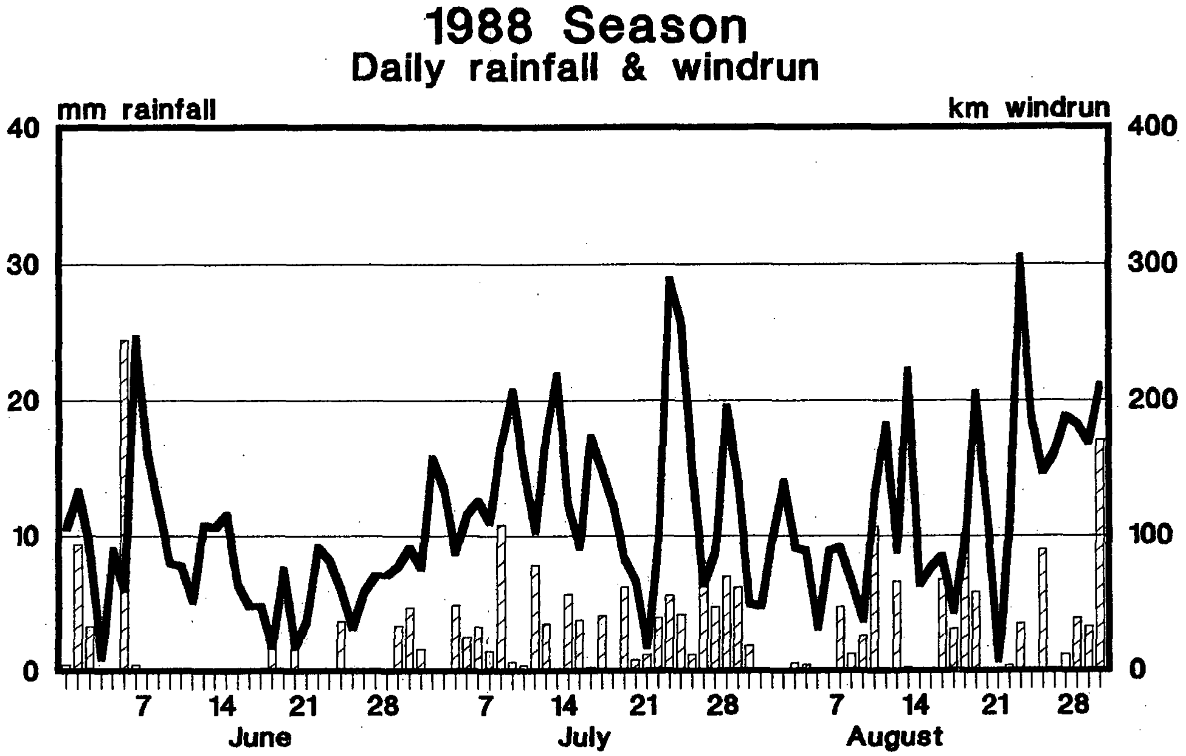
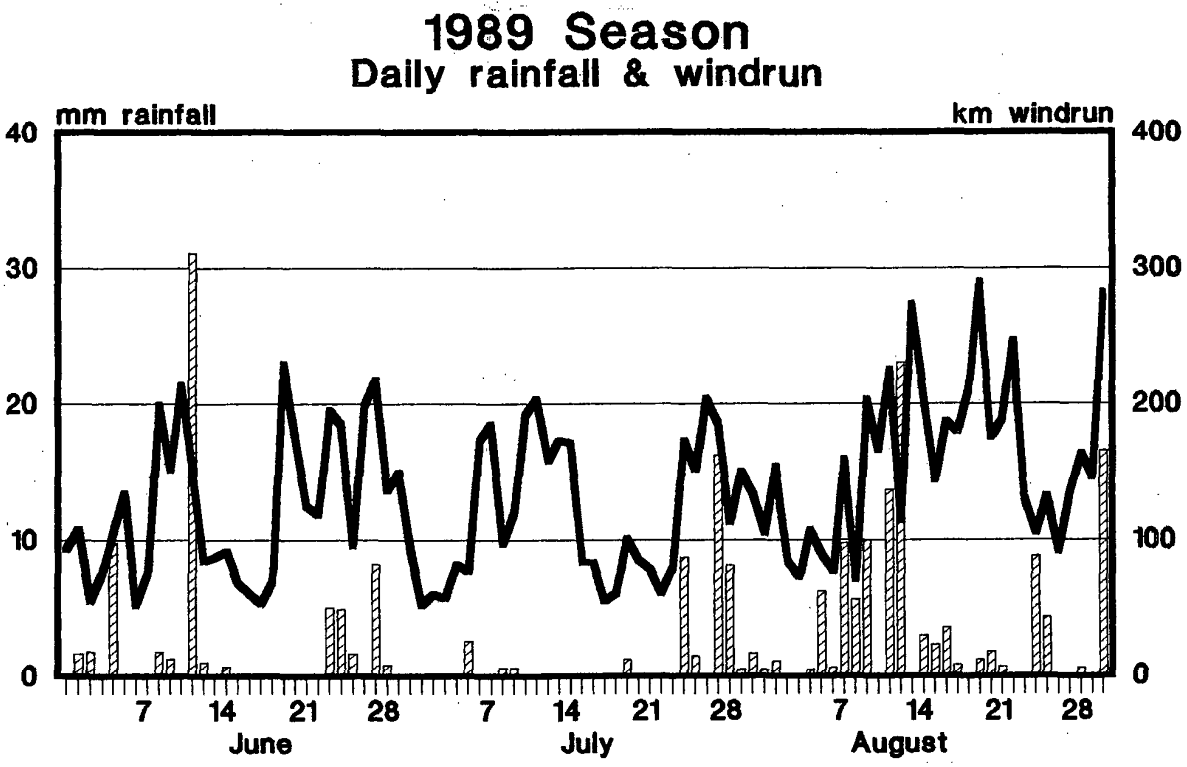


Figure 3.2



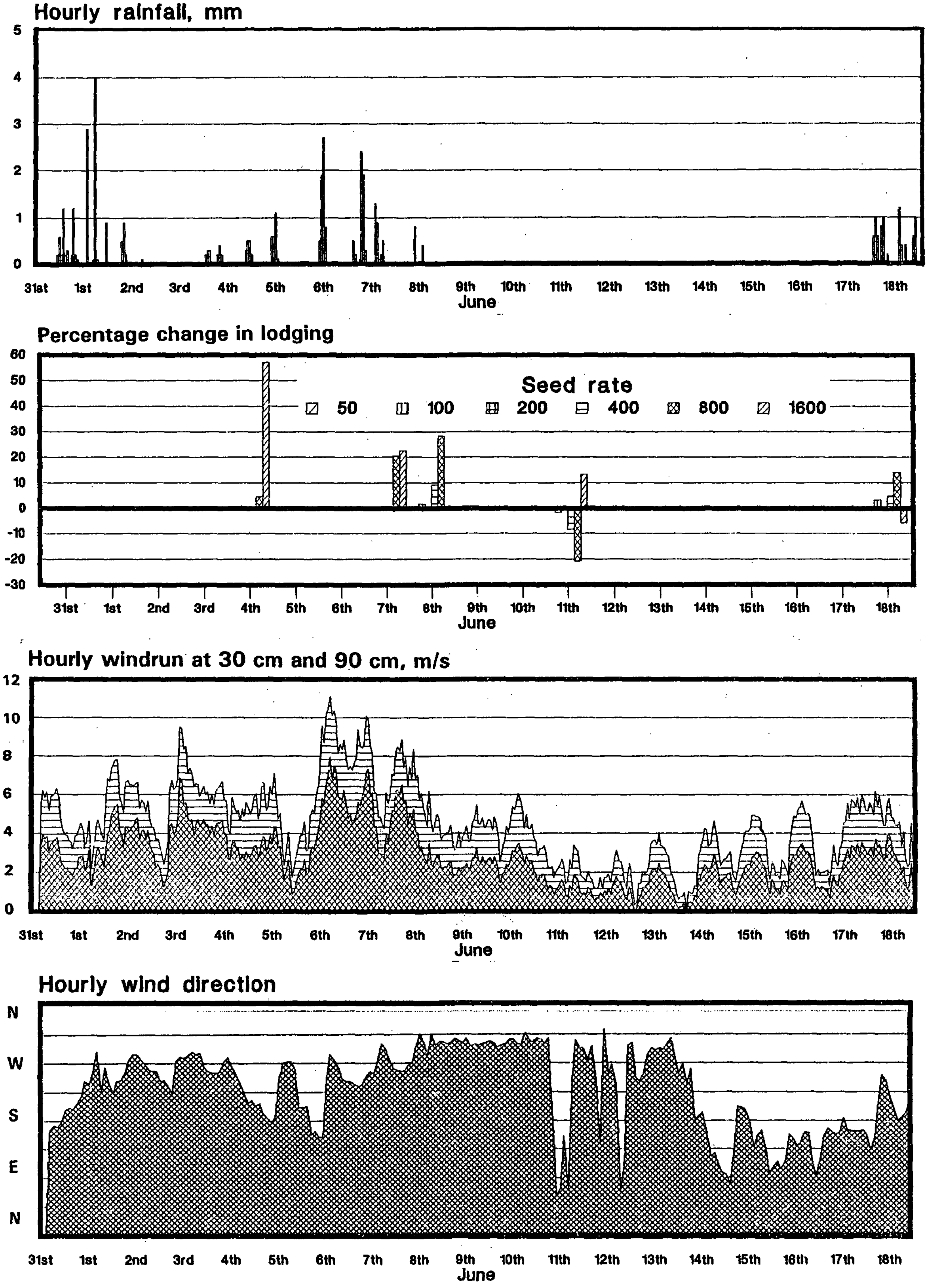


Figure 3.3

Weather and lodging, 31st May to 18th June 1990

Hourly rainfall, mm

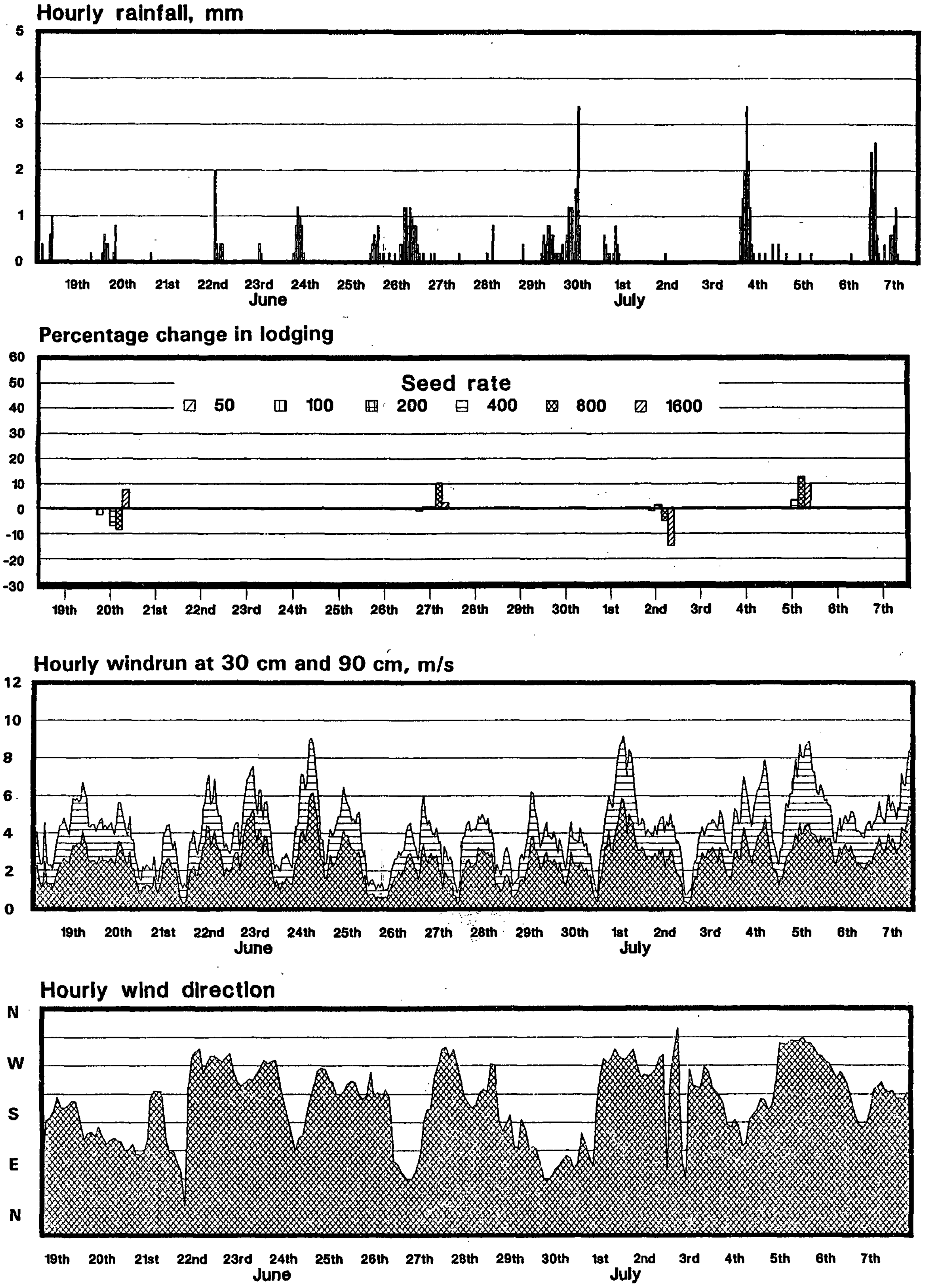
Percentage change in lodging

Hourly windrun at 30 cm and 90 cm, m/s

Hourly wind direction

Figure 3.4

Weather and lodging, 19th June to 7th July 1990


Hourly rainfall, mm

Percentage change in lodging

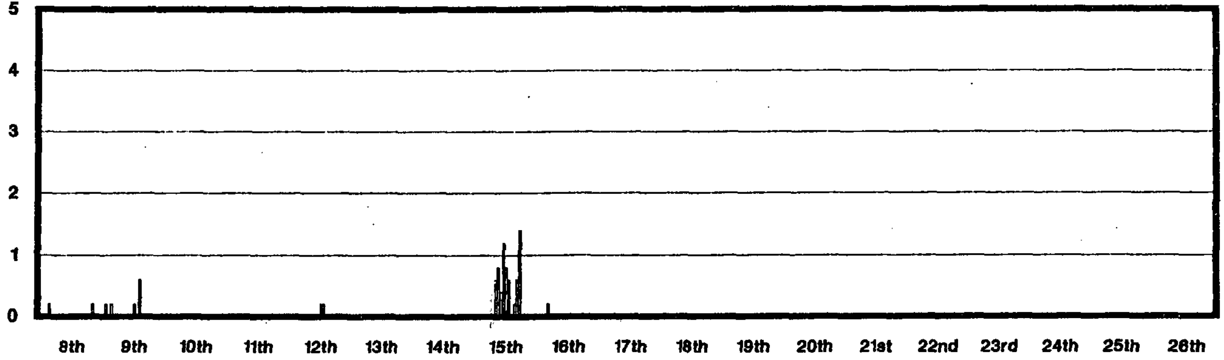
Hourly windrun at 30 cm and 90 cm, m/s

Hourly wind direction

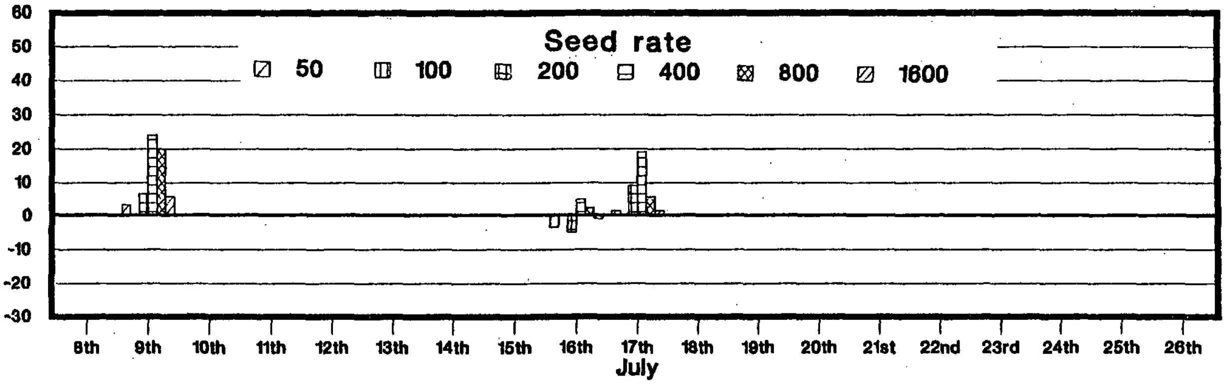
Figure 3.5

Weather and lodging, 8th July to 26th July 1990

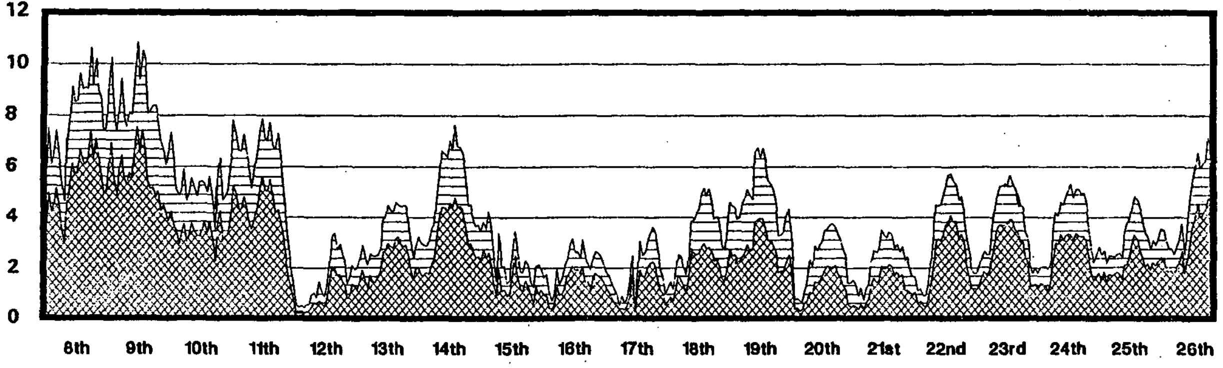
Hourly rainfall, mm



Percentage change in lodging



Hourly windrun at 30 cm and 90 cm, m/s



Hourly wind direction

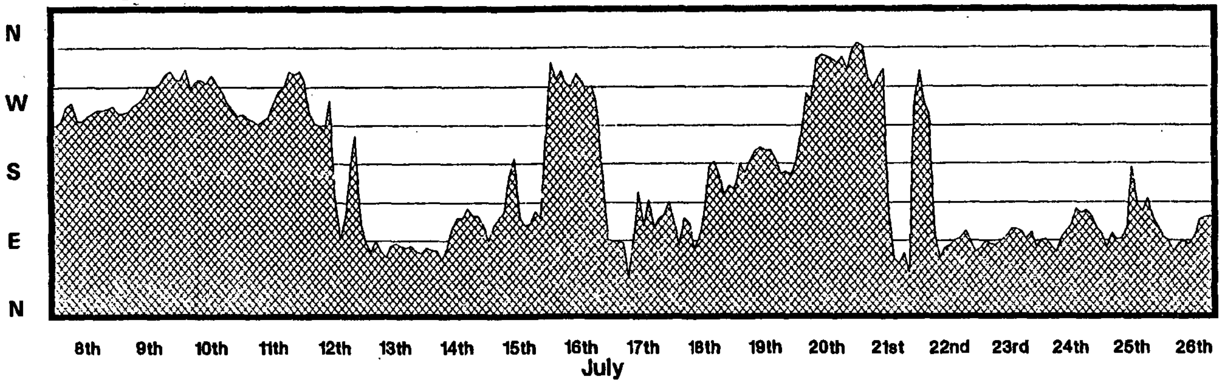
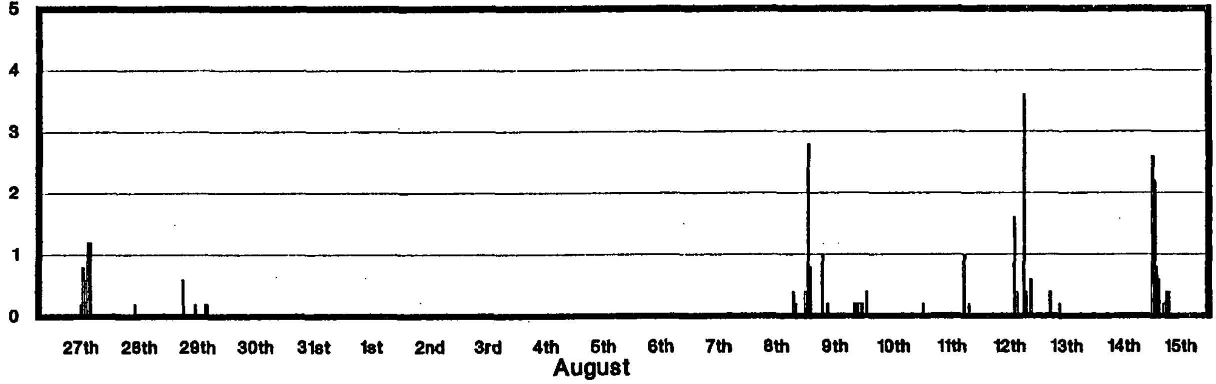


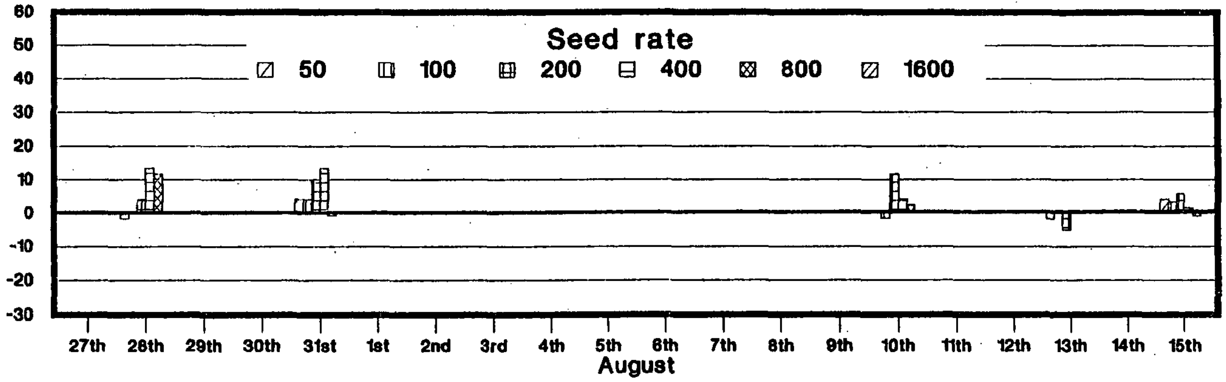
Figure 3.6

Weather and lodging, 27th July to 15th August 1990

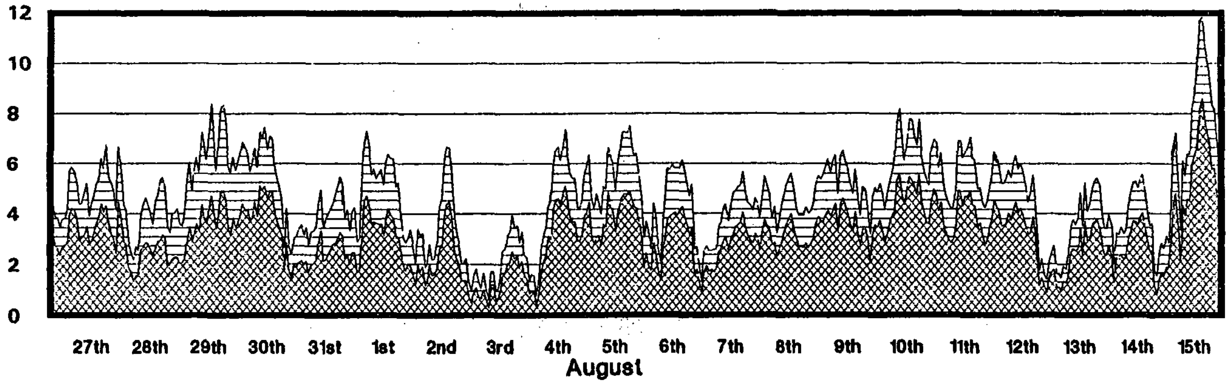
Hourly rainfall, mm



Percentage change in lodging



Hourly windrun at 30 cm and 90 cm, m/s



Hourly wind direction

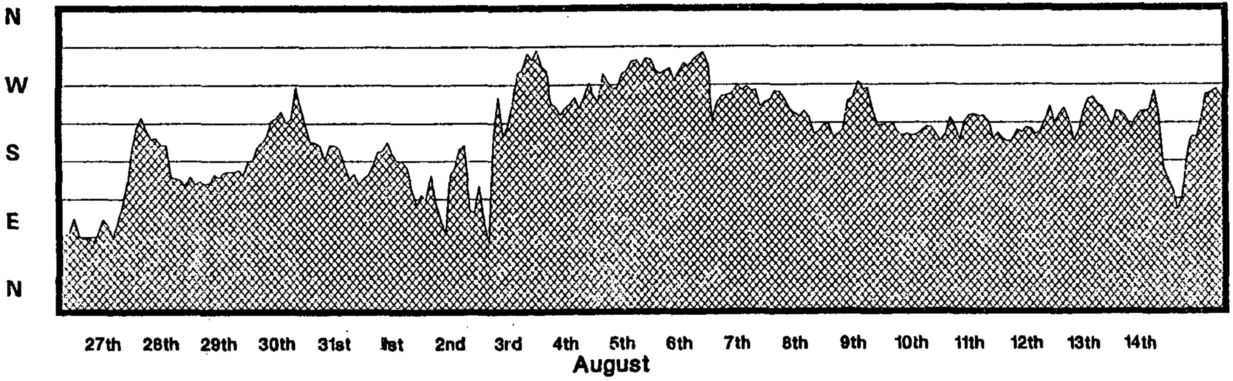
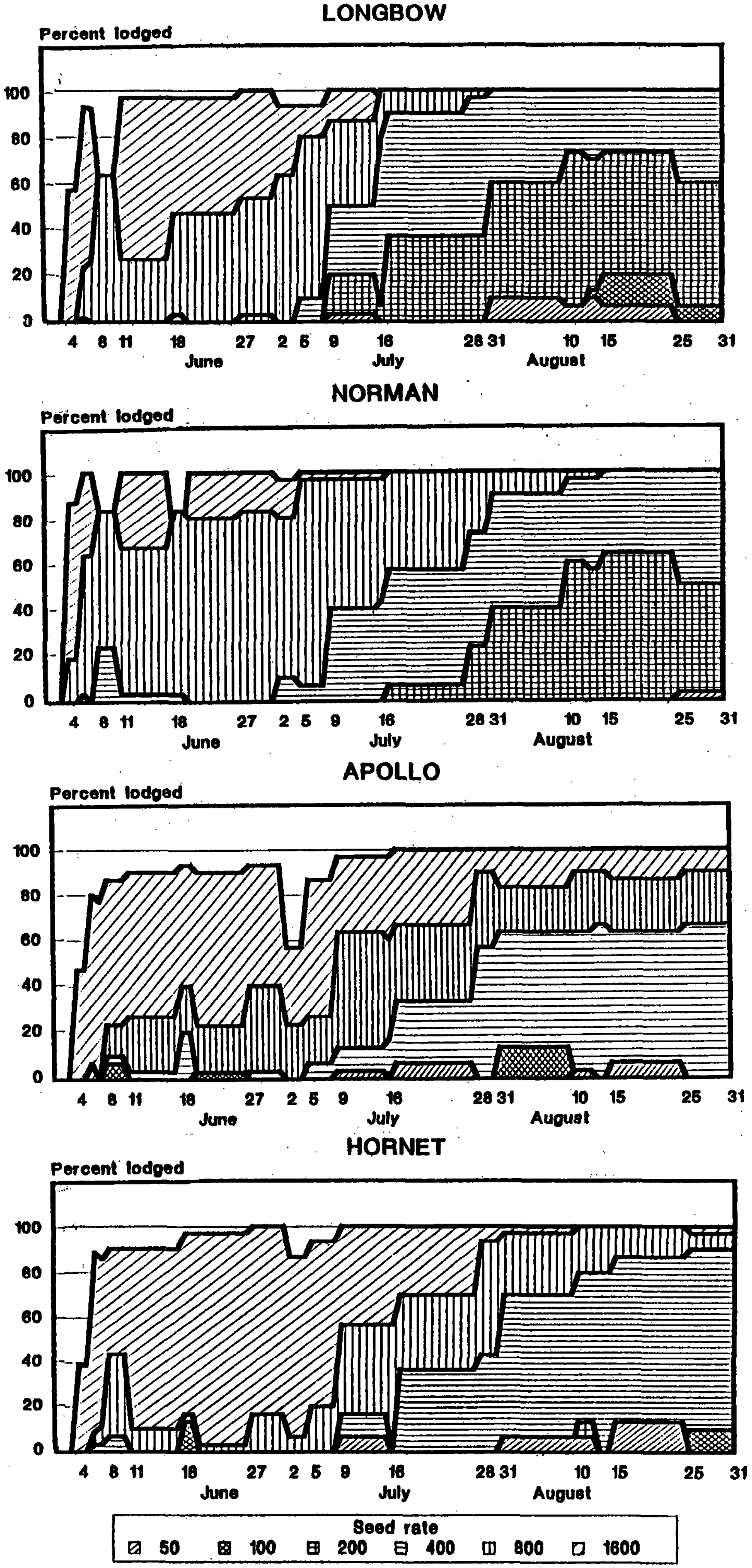


Figure 3.7

Lodging Score



Chapter 4

The Aerial/Shoot System

The morphology and anatomy of the stem

Lodging is most likely to occur and is most damaging during grain filling. Elongation of the five to seven internodes of the stem is completed shortly after anthesis. A number of additional internodes, typically five, do not normally elongate and form part of the crown. In the majority of wheats grown in the United Kingdom the internodes are hollow and taper towards their ends but the stem has a solid cross-section at the nodes. The leaves are joined to the stems just above the nodes, and are wrapped tightly around the stem for a short distance forming the leaf sheaths. The leaf bases are swollen, giving the stem an overall increase in diameter in the nodal region. The internodes of the plants tend to become longer from the base upwards, with the penduncle, which can continue to grow after anthesis, being up to half of the total stem length (Percival, 1921).

The material properties of the stem

The most commonly considered material properties of the stem are those of stiffness, strength and flexural rigidity. Stiffness is a property of the material from which something is made, and is ultimately dependent on the bonds between the molecules of which it is composed. It is entirely independent of the macroscopic geometry of the structure. Stiffness is defined as the ratio of stress (the load applied per unit area to a structure), to strain (the proportion of the original dimensions by which the structure deforms). In linearly elastic materials stress is linearly proportional to strain, and assuming conservation of shape and volume, the constant of proportionality is Youngs Modulus of Elasticity, E.

Strength is the load at which a structure breaks. Every structure has its own individual breaking load. Strength is related to the material properties and the geometry of the structure. Flexural rigidity, the tendency of a columnar structure to bend, is governed by its stiffness (E) and geometry (I), the second moment of area of the cross section. 'I' is purely a geometric property and is independent of the material.

There are many techniques for determining these properties experimentally. A number of workers have attempted this with varying degrees of success (Graham, 1985; Neenan and Spenser-Smith, 1975; Oda *et al.*, 1966; Ennos, 1991; Stanca *et al.*, 1979). Typical values of E are between 0.25 and 0.8 $\mathrm{MNm^{-2}10^{4}}$, and EI between 1 and 12 $\mathrm{Nm^{-2}10^{-2}}$. Values of strength vary greatly and comparisons are hardly possible. It is not clear whether this variability is due to technique or the basic variability of the material.

Studies have shown that the flexural rigidity of wheat plants increases down the plant, though it seems to be a point of some contention as to whether this is due to stiffness or geometrical factors. The base of wheat plants is therefore very rigid and will act as an effective lever. Stiffness of the wheat plant material increases as the plant ripens. This can clearly be seen in the field. A ripe wheat crop shows much less movement in response to the wind than does a similar green crop. Despite the fact that nodes are structurally considerably different from the internodes, and have very little "mechanical tissue", bending tests across the nodes have shown that these areas have very similar flexural rigidities to adjacent sections of internode (Graham, 1985).

The material properties of grass leaves have been thoroughly investigated in relation to silage cutting and grazing (Vincent, 1982), however, it would be difficult to integrate this information with work done on wheat stems. As was mentioned above, some areas of the stem are tightly wrapped in a leaf sheath. This should be capable of lending support to the stem, especially during early elongation, when the stem is less rigid. Testing of mature stems with and without leaf sheaths by Graham (1985) failed to show differences in flexural rigidity. By this stage the leaf sheath is no longer as tightly wrapped about the stem, and is unlikely to play a role in support. Niklas (1990), however, concluded from an experiment on two cultivars of *Avena sativa* that leaf sheaths did contribute significantly to flexural rigidity of internodes at various stages during crop development. If the leaf sheaths of wheat plants were demonstrated to provide additional support this would make it less likely that stem failure would be a cause of lodging.

Failure of the wheat stem structure

When the stem is subjected to bending forces it can fail in one of two ways. By breaking in tension, and by breaking in compression. When a stem is bent it has a radius of curvature. Stem material on the outside edge of this radius of curvature is in tension, and stem material on the inside is in compression. Between the two there is a neutral axis where no stresses occur. Since wheat stems are very strong in tension, it is unlikely that this form of failure will occur unless the stem has already been weakened by disease or physical damage.

Compression of the stem can lead to stem failure by buckling. Buckling can occur in two forms - 'Local' buckling and 'Euler' buckling. It is normally accepted that wheat stems are most susceptible to failure due to local buckling of the lower culms (Neenan and Spenser-Smith, 1975; Graham, 1985). This occurs when excessive bending stresses lead to flattening and kinking on the compression side of the stem. This allows the structure above the kink to topple over. The phenomenon is described by Equation 1. Experiments have shown, however, that local buckling stresses cannot be correlated with lodging susceptibility and observations show that this phenomenon is rare in the field.

$$(1) \qquad R_l = \frac{kEI}{D} \qquad \text{where}$$

R_l = Buckling stress
E = Youngs modulus
D = Diameter
k = Constant (0.5, Wainright *et al.*, 1976)
I = 2nd Moment of inertia

Euler buckling arises when bending forces due to the wind cause the stem, which is considered to be under axial compressive loading due to its own weight, to buckle. Length, elastic modulus and geometry of the stem will determine the critical buckling stress (Equation 2).

$$(2) \qquad F_e = \frac{Pi^2EI}{4L} \qquad \text{where}$$

F_e = Critical buckling force
E = Young's modulus
I = 2nd Moment of inertia
L = Length of the plant

This theory of Euler bucking is based on the assumption that the stem is a hollow tapering rod of uniform material. This assumption falls short of being an adequate description of the wheat stem because:

i) The wheat stem is not a single member but is made up of a number of internodes, each of which has different properties.
ii) The stem does not have a uniform taper.
iii) The stem is not composed of a single uniform material, but is a composite with fibres embedded in a matrix.
iv) The stem is unlikely to be linearly elastic (ie obeys Hooke's Law), but is more likely to behave as a visco-elastic composite material.
v) The stem is not hollow and open at both ends. It has solid nodes which seal each internode.
vi) The stem wall thickness is not less than one twentieth of the stem diameter.
vii) Wind loading is unlikely to be a steady force, but rather tends to fluctuate in direction and intensity.

Furthermore the properties of the stem change with time as the plant matures and also with environmental conditions such as moisture stress.

Column theory also has problems in coping with the wheat stem as it is formulated to deal with rigid structures which undergo only small deformations. By comparison a wheat crop in high winds will undergo large deflections which give rise to greater moments at the stem base due to the increased influence of the weight of the head.

The aerial shoot system needs therefore be viewed as a complex structure composed of a number of visco-elastic members with internodes of varying dimensions and properties as the plant grows and matures, joined end to end and supporting the ear which has fixed ultimate dimensions but variable mass. This structure is wind loaded differentially down its length, from top to bottom, according to the wind speed profile.

The influence of the stem, ear and leaves on lodging

The interaction of the wind and the aerial parts of the plant results in the forces which threaten the stability of the whole plant. The stem resists the bending forces generated as a result of the wind and the weight of the aerial parts of the plant, and transmits these forces, in the form of a force and a moment, to the base of the plant. Leaves will shed wind in the manner of flags rather than catch the wind in the manner of sails (Grace, 1977; Rutter, 1966). However, the drag produced and the weight of the leaves will contribute to the force and moment around the base of the wheat stem. The material and structural properties of the stem to a large extent govern the magnitude of these forces at the stem base.

The ear has a two-fold influence on the force and moment generated at the base of a wheat plant. The complex geometry of the ear, with its many ridges and surfaces give it high drag properties. Consequently, the ear interacts more strongly with the wind than the rest of the plant and gives rise to a high proportion of the initial bending force which displaces the plant. This force is described by Equation 3. The area of the head has been found to be 8+/-2.3 cm^2 .

(3) Force= kAV^2 where
A = Area of head in cm2
V = Wind velocity in m/sec
k = 0.0066

The ear also acts as a weight, which increases by up to thirty percent during periods of rainfall due to the ability of the ear to trap water (Table 3.1 and Neenan and Spenser-Smith, 1975). This will increase the force and moment experienced at the stem base when the stem is displaced.

Behaviour of the wheat stem under wind loading

In order to calculate the force and moment at the base of the stem and hence the forces passed onto the root system, it is necessary to understand the behaviour of the structure under windload. The force transmitted to the stem by the wind has been investigated using wheat plants in wind tunnels (Neenan and Spencer Smith, 1975; Graham, 1985; Oda *et al.*, 1966).

The stem is usually considered to be a column in equilibrium. Generally a load carrying structure is said to be in a state of stable equilibrium if, for all admissible small displacements from the equilibrium position, restoring forces arise which tend to accelerate the structure back towards its equilibrium position (Saada, 1974). The bending moment can be related to the material and geometrical properties of the stem and the amount by which it is displaced (Equation 4). The moment about the base of the stem is proportional to the force generating the moment and the length of the lever by which it is transmitted (Equation 5).

(4) $M = \frac{EI}{R}$ where
R = Radius of curvature
E = Young's modulus
I = 2nd Moment of inertia
M = Bending moment

(5) Msb = F L where
Msb = Moment at stem base
F = Wind loading
L = Height at which force is considered to be acting

Since the stem has a mass (i.e. an ear) on top, once it has been deflected from its equilibrium position by the wind, it is further displaced by the weight of this mass and by the self weight of the stem. The greater this deflection, the greater will be the component of the ear weight which can generate moment. The deflection of a cantilever in this way can be described by Equation 6.

$$(6) \quad S_{max} = \frac{1}{3}\frac{WL^3}{EI}$$

where

W = Weight of load
L = Length of the lever
E = Young's modulus
I = 2nd Moment of inertia
S_{max} = Deflection

Greater rigidity will reduce bending of the culm and, as well as making stem buckling unlikely, should reduce the moment at the stem base by preventing the weight of the ear generating moment. Selection of shorter stems also reduces the moment at the base of the stem by shortening the lever.

This strategy has indeed resulted in increased wheat yields since its first inception in the 1920s, and was particularly marked with the introduction of dwarf and semi-dwarf varieties. The introduction of these varieties in the 1960s resulted in almost a doubling of wheat yields in Mexico (Borlaug, 1983), and a significant increase in the wheat yields in Britain where previously they had stagnated. In trials short stiff varieties are usually less susceptible to lodging (Stanca *et al.*, 1979). However, such yield increases are more likely to be due to the redistribution of the plant's resources to the grain and away from the straw and other similar factors rather than to reduced lodging alone.

Energy absorption and damping

Due to its elastic resilience, which is the ability to absorb, store and release energy without sustaining damage, the stem will behave as a shock absorber, and in so doing reduce the moment at the base of the stem. It can be thought of as the total amount of strain energy, which can be stored in a bent stem, without inducing local buckling. Energy absorption potential of the stem is increased by the presence of the solid nodes at the leaf bases. Any energy absorbed by the stem in bending will not be transmitted to the stem base. Cellulose, which forms a high proportion of the material of the stem, has a very high elastic resilience of about 10MJm^{-3}, far superior to that of spring steel. Maximum resilience is given by a tube of uniform structure under tensile loading (Equation 7).

$$(7) \quad \text{Energy Absorption} = Sf^2 \frac{AL}{2E}$$

where

Sf = Failing stress
L = Length
A = x sectional area
E = Young's modulus

The force and moment experienced at the base of a wheat plant in the field is likely to be less than the theoretical value for a single stem, due to energy being dissipated by damping as adjacent stems come into physical contact with one another. Individual stems have a natural frequency at which they will oscillate when displaced by a gust of wind. When an oscillating stem is subjected to a further gust of wind the oscillation may be reinforced or disrupted depending on whether or not the movement of the stem is in phase with this further gust. The limited trials conducted in this project showed that damping has indeed a significant effect, reducing the amplitude of oscillations buy up to 2/3 in the direction of the wind.

As wind is not a steady unidirectional flow but consists of gusts which may vary in direction, frequency, amplitude and duration this will make the damping effect greater. When adjacent stems move in phase with one another there will be minimum contact between them and the full potential displacement will occur. When adjacent stems become out of phase a proportion of the energy is dissipated through contact (as in Newton's cradle) and the displacement is consequently reduced.

At this stage it has been established that the basic stem properties of length, weight, elasticity as a whole and of individual internodes, geometry and flexural rigidity including leaf sheaths; ear properties of weight and area; leaf properties of area and weight and population properties of damping and visco-elastic creep all contribute to the lodging phenomenon. The relative importance of each property and variations in magnitude due to ontogeny and environmental and management effects need to be determined in order to produce a succinct and useful model.

Chapter 5

Experimental work on the aerial shoot system and its properties

At the start of the project it was believed that stem breakage or buckling was the most likely cause of lodging in the field. Bending tests were carried out to determine the stress and displacement of whole wheat stems and of their component internodes up to breaking point. Stem geometry measurements were taken to determine the 2nd Moment of Inertia (I). It was thought that by determining the radius of curvature of the whole stem at its breaking point it would be possible to determine the wind deflection required to bring about lodging in the field. Data on the material properties could also be used to calculate the forces transmitted to the root soil system from the aerial shoot system.

Whole stem bending tests

A methodology was developed for conducting stem bending tests using an Instron material testing rig to measure experimental load and displacement. The main problems were in the design and construction of a suitable method of attaching the plant material to the experimental apparatus and of transmitting a load from the load cell of the Instron to the plant material in a way consistent with natural loadings.

The design developed was to mount the plant vertically on a horizontal beam to the side of the Instron with the base of the stem held in a split cork inserted into a metal ring (Figure 5.1). The stem could be moved down through the cork so that testing of successive internodes could be carried out. The force was applied horizontally to the stem just below the ear, via nylon monofil attached to a sliding collar through which the stem had been inserted. The monofil passed over an eccentric cam which allowed the force to remain approximately horizontal as the stem bent. A series of low friction pulleys was used to guide the monofil to the load cell of the Instron.

The Instron was set to move through a set displacement of the stem in a time of approximately one second. The displacement was increased by stages from a minimum, giving an angle of stem movement through 35°, until the displacement resulted in breakage of the stem.

Table 5.1

Breaking load for whole wheat stems, 1988

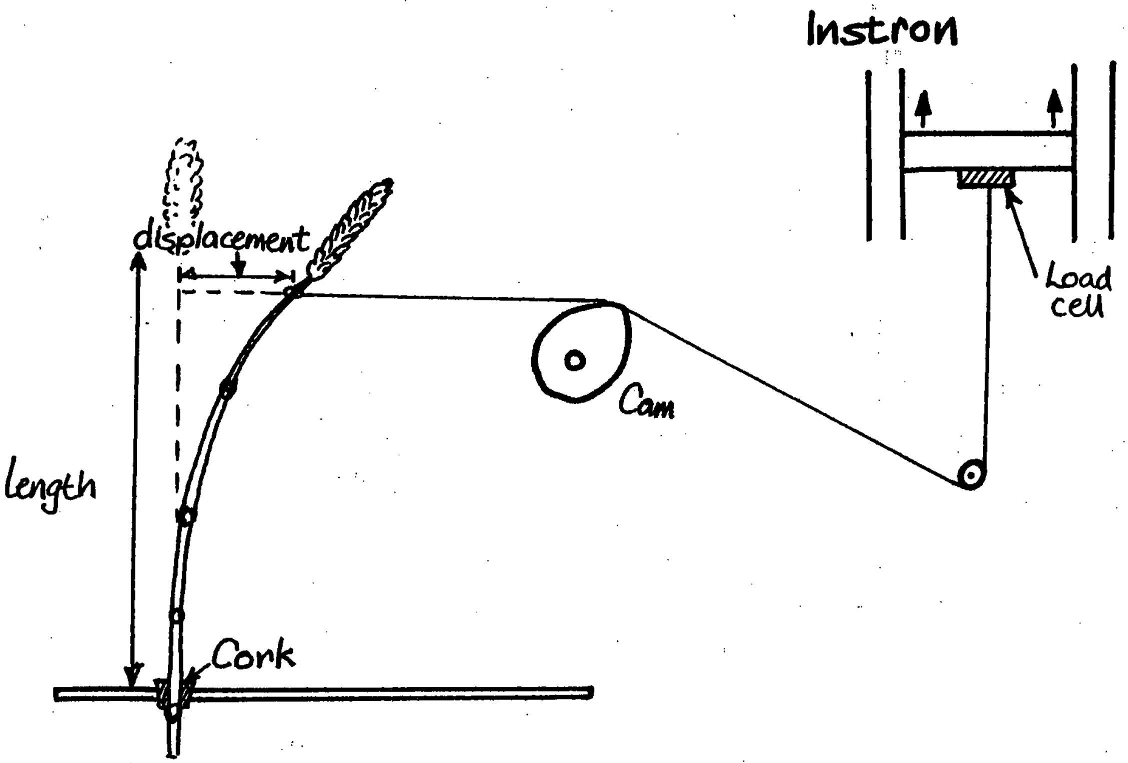
Internodes (from top)	Diameter of added internode (mm)	Total Length (cm)	Breaking Load (g)	Displacement from vertical (cm)
1	3.52	28.06	477.6	27.02
1,2	4.46	45.80	401.7	35.60
1,2,3	4.45	56.91	310.2	47.07
1,2,3,4	4.32	64.30	383.9	63.84
1,2,3,4,5	3.61	70.91	436.8	73.02

Thirty stems from the control plots of Slejpner in the 1988 Growth Regulator Experiment were tested in late June the processing being carried out on the day of sampling.

The results were very variable from stem to stem. Very large displacements occurred at breakage (Table 5.1) which was a single decisive event consistent with local buckling. The break point was

Figure 5.1

Test rig for whole stem bending



distinctive and was situated low on the stem. The displacements needed to cause failure of the stem structure by buckling were greater than those likely to occur in the field as a result of the action of wind. The field observations of lodging which had already been taking place over the 1988 season also indicated that lodging was not usually the single decisive event which would be associated with buckling.

Internode bending tests

In order to model the stem as a composite structure made up of a series of nodes and internodes it was recognised that data on the mechanical properties of each internode was required, i.e. Young's Modulus and the 2nd Moment of Inertia.

Following consultation with Queen's University Mechanical Engineering Department a method for determining the properties of each internode individually using standard three point bending tests (Jensen and Chenoweth, 1983) was established.

Deflection = $PL^3/48EI$

P = Applied load
E = Young's modulus
I = 2nd Moment of inertia
L = Distance between supports

The internodes were prepared as in the stem geometry study (See following section) and tested across two supports which were 10, 20 or 40mm apart depending upon the length of the internode being tested. The bending force was applied by an Instron which recorded the load and displacement until the point of failure.

During the 1989 field season ten plants were sub-sampled from half metre rows in the 250 kgN/ha and 150 kgN/ha treatments in late July. At the time of sampling the plants had already started to ripen. The results (Table 5.2) therefore represent the transition stage between the green stem in which 'strength' may have been greater and the 'ripe' stage in which 'rigidity' may have been greater. Each internode was subjected to a three point bending test to destruction using the Instron.

Table 5.2
Breaking load for wheat internodes, 1989
(Three point bending test, 20 mm between supports)

Internode	Diameter (mm)	Load (kg)	Displacement (cm)
250kg N/ha			
1	3.90	3.32	1.81
2	3.72	3.11	1.78
3	4.82	5.36	1.95
4	4.32	6.02	1.81
150kg N/ha			
1	4.89	4.53	1.93
2	4.70	4.54	1.86
3	4.66	6.94	2.35
4	4.39	6.86	1.92

Samples from the variety plots of Norman and Longbow during the 1990 season were taken in early and late July representing the mid-point of grain filling and early senescence and subjected to the same tests, the results being presented in Table 5.3.

The graph generally followed an almost linear line to the peak showing that the internode behaves according to Hooke's Law up to the point of breakage. The internode diameters and the breaking loads were very similar in the samples from both seasons and between the varieties. Breaking load increased in the older, thicker internodes in all treatments and was greater at the lower N rate than at the higher N rate in 1989. The displacements observed were very similar for all internodes and at both N rates. Although there was a significant decline in the maximum displacement as the material progressed through senescence in 1990, indicating a decline in the elasticity of the straw, there was little change in the breaking load the material could withstand.

Stems of plants grown at lower N rates will bend less in response to a given wind loading than stems in plants grown at higher N rates thus generating a smaller bending moment. Differences between Longbow and Norman in their susceptibility to lodging are not attributable to elasticity or geometry as shown by the similarity of these properties in their upper four internodes. The smaller differences observed in the more mature internodes are in agreement with previous findings that stiffness increases as the plant ripens. These data will be of use in calculations of the moments acting at the base of the plant.

Table 5.3

Breaking load for wheat stems, 1990

(Three point bending test, 20 mm between supports)

Internode	Diam. (mm)	Load (kg)	Displ. (cm)	Diam. (mm)	Load (kg)	Displ. (cm)
Norman		Early July		Late July		
1	3.78	3.94	3.75	3.52	3.68	2.74
2	4.82	4.53	3.80	4.85	4.71	2.36
3	4.64	6.18	4.35	4.74	6.05	2.73
4	4.42	6.11	3.82	4.54	5.97	2.44
Longbow						
1	3.75	3.64	3.60	3.68	3.83	2.84
2	4.83	4.43	3.61	4.69	5.05	2.56
3	4.52	6.00	4.26	4.71	6.10	2.90
4	4.41	6.31	3.79	4.66	6.21	2.80

Significance: Diameter NS, Load NS, Displacement NS, Date ***

Stem morphology

Length, diameter and fresh weight of the internodes and ear all play a role in generating the moment at the base of the stem. Many of the factors known to influence the occurrence of lodging, such as variety, nitrogen level, growth regulators and seed-rate, have an effect on these morphological characteristics. The propensity to lodge also increases over the period of grain filling. Data on ontogenetic changes in the characteristics and the effects of management factors will be useful in determining their relative importance where lodging incidences vary.

Samples of wheat plants were obtained by pulling up by hand a half metre row length from each of four high N (250 kg/ha) plots and four low N (150 kg/ha) plots. Samples were taken at weekly intervals between May and harvest. Ten plants were selected at random from this sample. The tillers of each plant were counted and removed.

Figure 5.2

1988 Internode lengths
on 7 weekly sampling dates

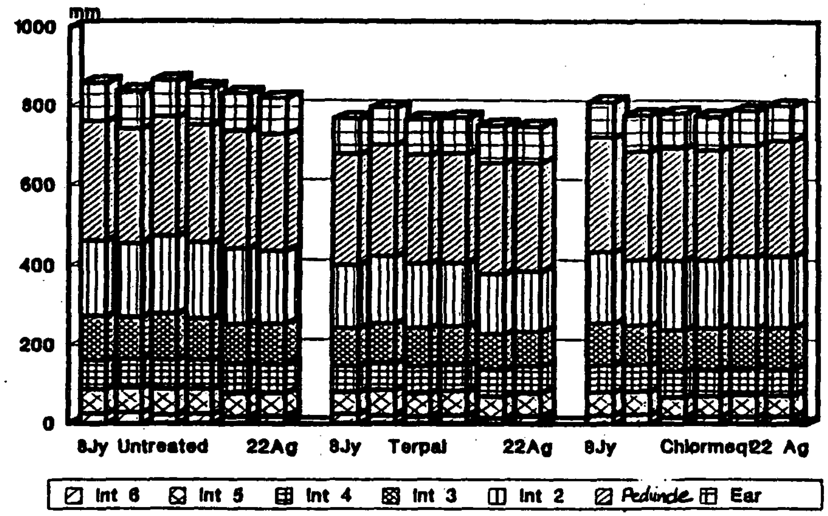


Figure 5.3

1989 Internode lengths
on 5 weekly sampling dates
at two nitrogen levels

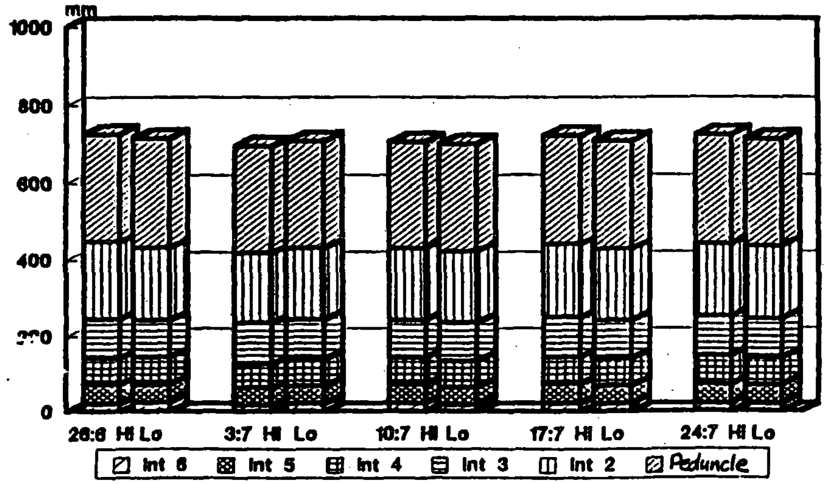


Figure 5.4

1988 Internode fresh weights

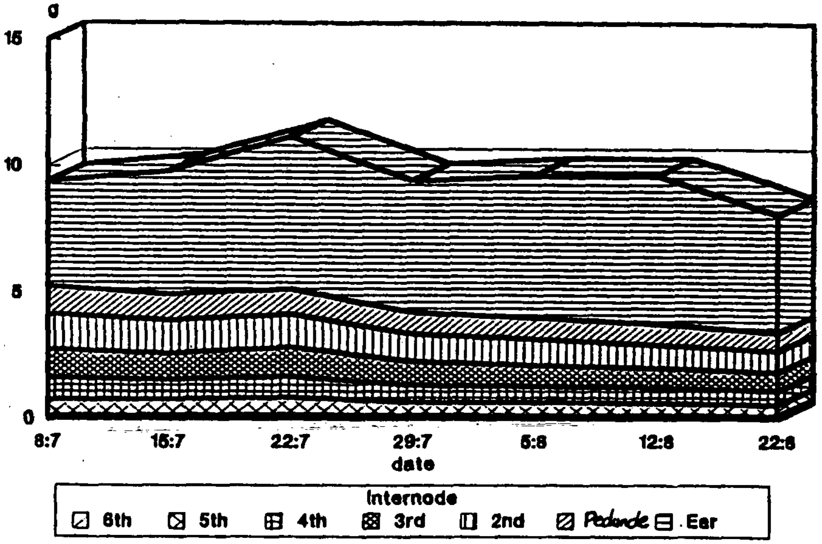


Figure 5.5

1988 Internode dry weights

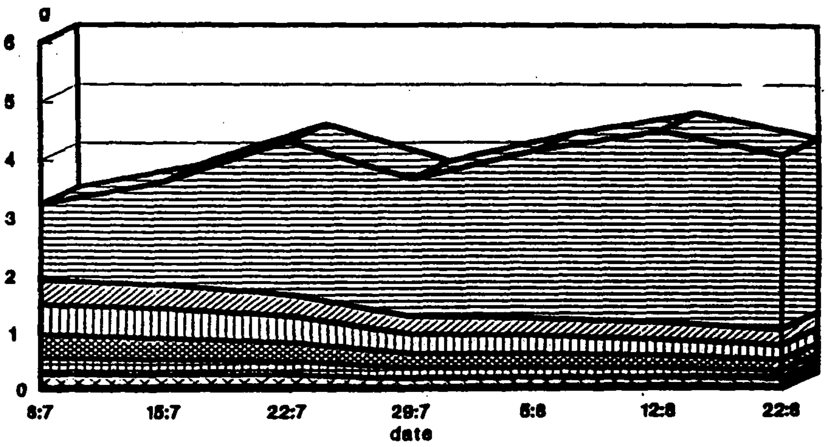
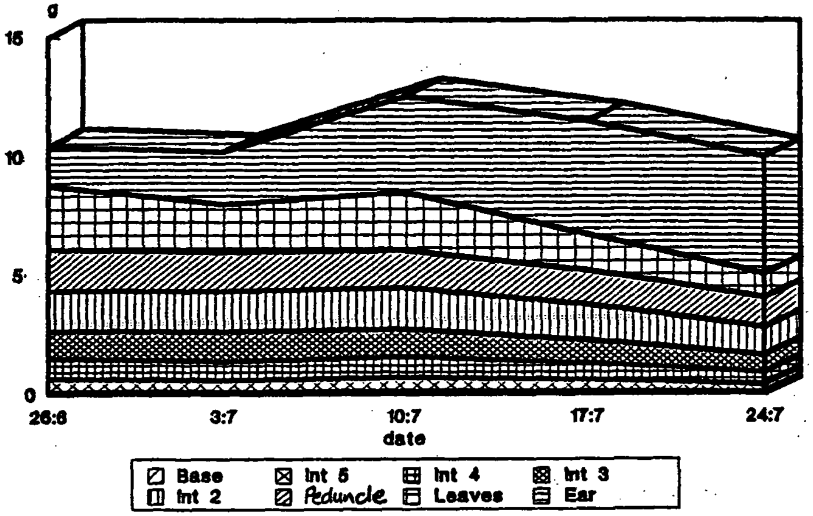


Figure 5.6

1989 Internode fresh weights

a) High nitrogen



b) Low nitrogen

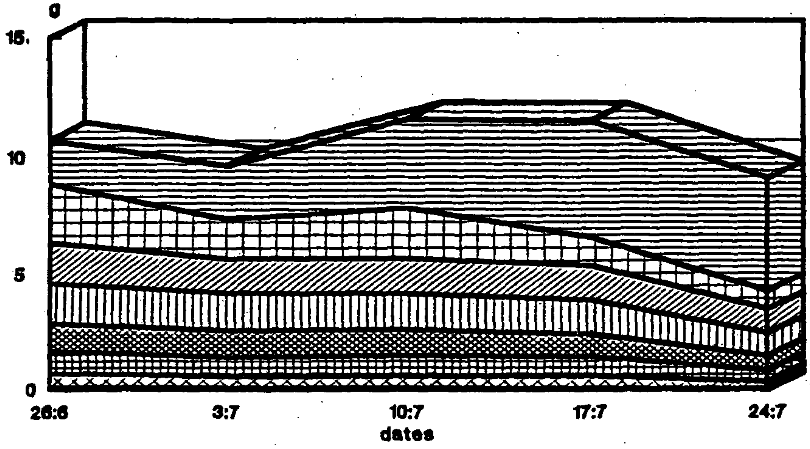
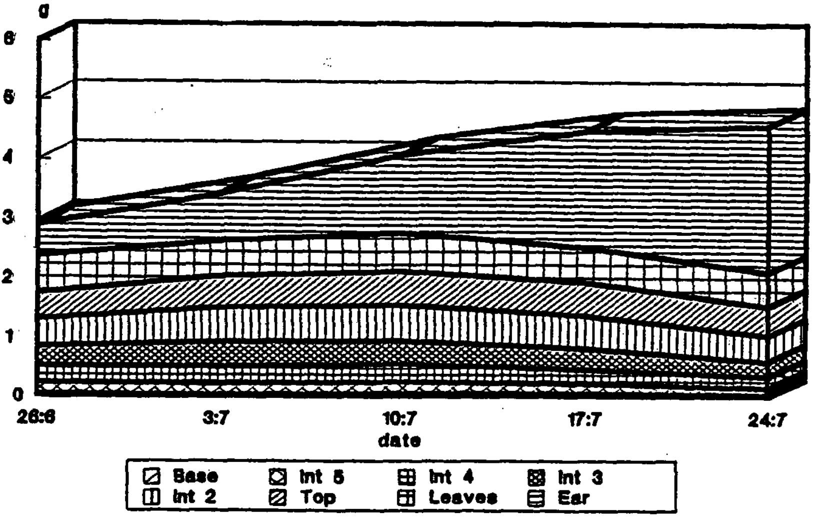


Figure 5.7

1989 Internode dry weights

a) High nitrogen



b) Low nitrogen

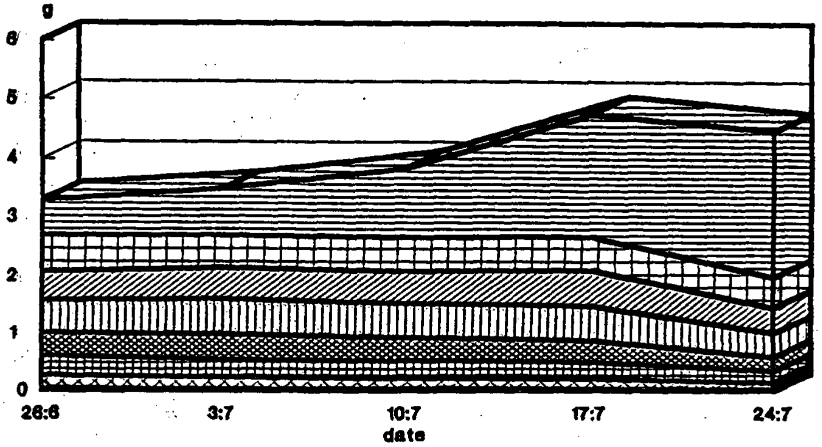


Figure 5.8

1988 Wheat Morphology

Mean Internode moisture contents

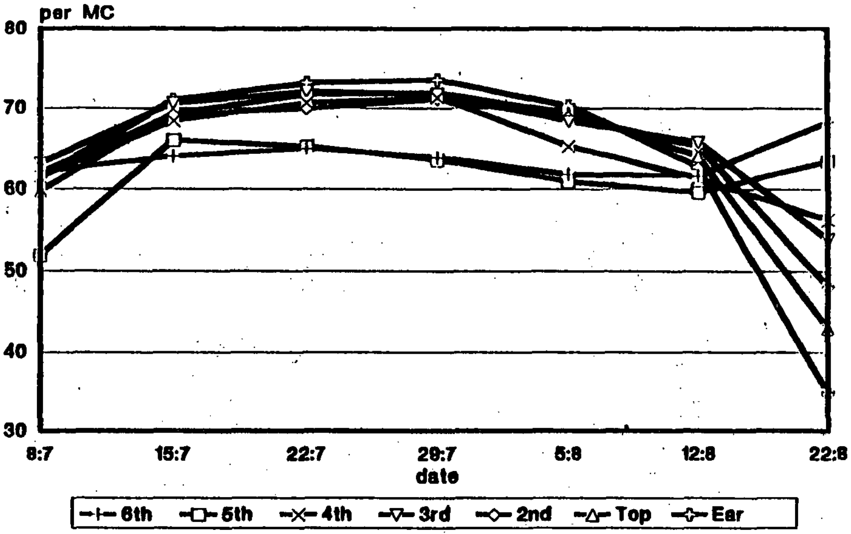


Figure 5.9

1989 Internode Diameters

Mean of 5 values per internode

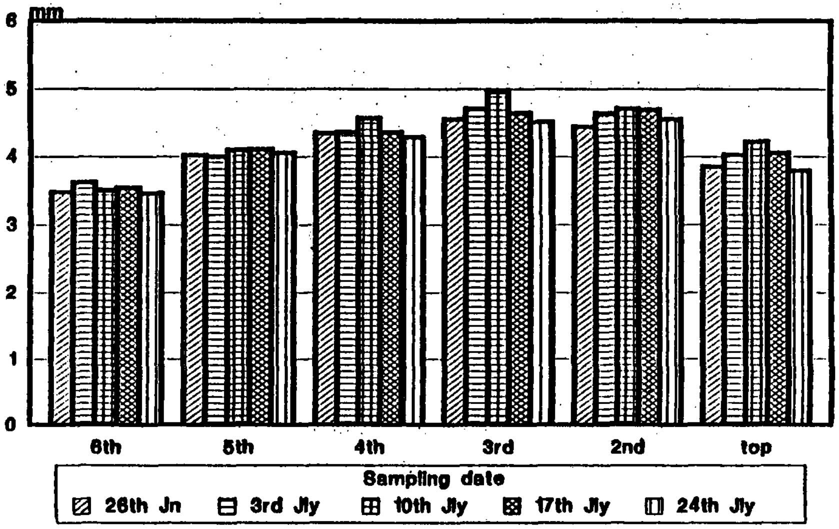
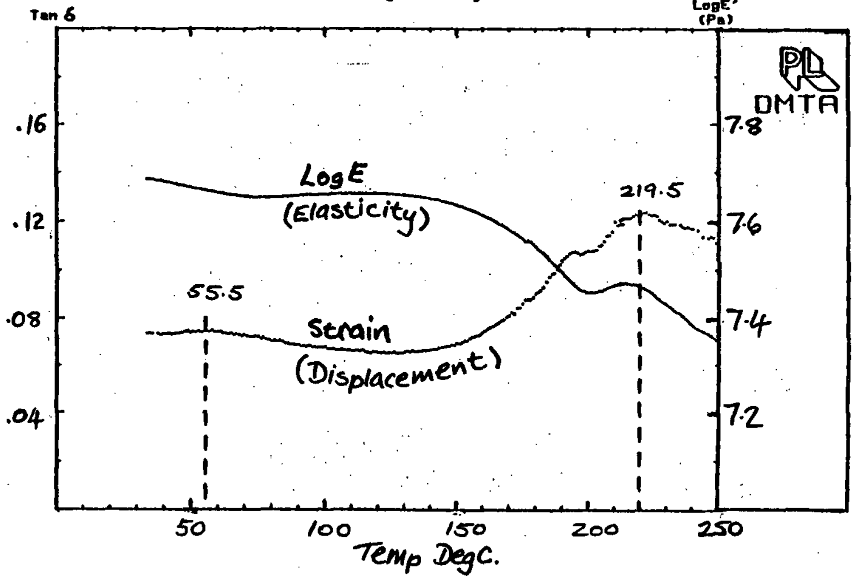


Figure 5.10

Visco-elastic creep testing of a wheat stem



The roots of the main stem were cut off at the base and the ear removed. Leaf laminae and sheaths were removed and weighed. The stem was then cut into individual internodes below each node. The nodes were numbered down from the top of the plant in order to provide consistency of numbering. Although the lowest internodes are botanically the first produced they are usually compressed together and difficult to separate. In this study a maximum of six internodes were dissected out.

For each main stem, length, fresh and dry weights of each internode were recorded along with the fresh and dry weights of the leaves and of the ears following emergence. The dry weights were obtained by drying for 16h at 80°C in a forced draught oven. The methodology followed in 1989 was the same as that in 1988 except that as the tightly wrapped leaf sheaths were thought to contribute to the material properties of the internodes only the leaf laminae were removed.

The peduncle (Internode 1) was the longest internode and length decreased down the stem to the basal internode (Figures 5.2 and 5.3). Diameter (Figure 5.9) and fresh and dry weights decreased down the stem between internode 2 and the basal internode. The peduncle had a similar fresh weight to that of Internode 3 and a similar diameter to that of internode 5 (Figures 5.4 to 5.7). The moisture content pattern from 1988 when sampling continued up to harvest showed the more complete ripening towards the top of the plants (Figure 5.8).

Fresh and dry weights of the internodes increased and then decreased over the sampling period, the losses being between 13% and 50% of their maximum weights and greater at the lower N rate than at the higher N rate in 1989. The ear increased in fresh weight for a longer period before beginning to lose weight towards harvest in 1988. Length was increased by greater N application and reduced by both Terpal and Chlormequat application but did not change during the periods of sampling.

Length as affected by nitrogen and growth regulator will play a role in determining their influence on lodging. Ontogenetic changes in length and diameter were minimal, but fresh and dry weights varied considerably. These weights, particularly those of the ear, will have a direct effect on the forces acting on the stem base. It could be postulated that weight might indicate changes in the biochemistry and cytology of the stem tissues which determine its stiffness. Its potential use as an indicator of changes in stiffness would have to be verified by further experimentation.

Visco-Elastic Properties

Complex composite structures such as stems undergo visco-elastic creep. This is the tendency for a structure, composed of viscous and elastic materials to become less elastic and more viscous (i.e. flowing), as a result of being stressed for a long period of time, or through many stress relaxation cycles. This means that the material properties of wheat stems will change with time as they are repeatedly stressed by the wind, or loaded by the ear, leaves and accumulated rain. Loss of stem rigidity and elasticity because of visco-elastic creep is a possible mode of failure leading to lodging.

The Instron being used in the first year was not suitable for cyclic testing to determine visco-elastic properties. Such assessments can be made using DTMA's. In these devices the material being tested is subjected to rapid vibrations during which the elastic properties are continuously monitored. Data can be collected over time to show progressive failure of the material. Increasing temperature is also used to accelerate the changes being observed.

While it was not possible within the financial resources of this project to run a complete set of samples through such a machine a single sample was tested with the assistance of Polymer Laboratories Ltd. The results of this test (Figure 5.10) indicate that the technique could be of considerable value in assessing the visco-elastic properties of the stem. The stem material tested did in fact show visco-elastic creep. The vibration had a frequency of 10 cycles per second and as the temperature increased above 150 °C the elasticity began to fall and the deflection increased. This indicates that the material is becoming floppier and less able to behave in an elastic manner. While in the field such high temperatures will not occur visco-elastic creep could still take place through repeated flexing of the stems over a period of time resulting in increasing floppiness and an inability to return to the vertical.

While this isolated test indicates that stems do undergo visco-elastic creep it still remains to be established that this mode of failure does or does not play a role in lodging in the field. If it does then further research would be needed to determine the factors which influence the visco-elastic properties of the stem.

Wind and stem movement

Although wind alone is unlikely to cause lodging through direct stem damage, the action of wind on the aerial shoot system is a key component of the forces arising in the root soil system. Some indication of the relationship between windspeed and direction and the extent of movement of the crop stand has been obtained in previous work (Neenan and Spenser-Smith, 1975; Graham, 1985; Oda *et al*, 1966).

Wind tunnel experiments were first considered as a means of further investigating the force transmitted to the stem by wind. However, in spite of the presence of an important aeronautics industry in Northern Ireland the only wind tunnels capable of imposing the relevant range of wind speeds were no higher than about 30cm and could not be used even with the most 'dwarf' of wheats.

The alternative approach was taken of monitoring the movement of wheat stands in the field and relating this to actual wind speeds recorded at the time. The movement of labelled wheat plants exposed at the end of a plot was filmed using a video camera while simultaneous wind data were recorded on an adjacent weather station. The method which was used is described in Appendix 3.

Over the period from June to early August 1989 when the crop was vulnerable to lodging the weather was exceptionally dry and wind speeds were low (see Figure 3.2). As a result there were no wind events that resulted in substantial stem movement or lodging. Some recording was carried out, including stem analyses, but detailed examination of the video recording was not considered to be of value.

Damping

Lack of stem movement in the observed plots could be largely attributed to the low wind speeds. Interaction of individual stems with their neighbours, i.e. damping was also taking place. The damping ratios for wheat stems when surrounded by varying numbers of adjacent plants were therefore investigated. In the literature the only related work on damping was on stands of sitka spruce carried out at the UK Institute of Sound and Vibration Research (White *et al*, 1976). This work provided the relatively simple techniques by which the effects of damping were investigated in this project.

Stands of wheat plants were chosen representing different crop densities and the number of stems per square metre counted. Up to five stems were selected in different parts of each plot and marked by means of a lightweight fluorescent disc placed over the top of the ear. Stem lengths were measured. A video camera was mounted on a gantry above each plot and during suitable wind events the movements in the crop were recorded looking vertically down on the ears for a 15 minute period. Scaling of the movement was facilitated by means of a 0.5m square quadrat placed on the ground. Simultaneous logging of the windspeeds and directions were made using the weather station. Plants surrounding the marked plants were then all removed and the movement of the marked plant alone recorded for a further 15 minute period.

To derive the damping ratio a number of gusts of similar intensity were identified for two 15 min periods for each plot. From the video recording these periods were identified and using acetate sheets over the video screen X and Y axes were placed over each marked ear, the rest position of the ear being the origin. Aligning the wind direction with the Y axis, the maximum displacements of the heads in the X and Y directions were then recorded. The results from each comparable gust for each plot were meaned and ratios in both the X and Y directions generated for each density of plant stand.

Table 5.6

Damping ratio of a wheat stand
(Approximate windrun, 10km/h)
Crop density 800 ears/m^2

	Parallel to wind	90° to wind
Displacement (Mean of 15 minutes)		
Damped	+/- 14.2cm	+/- 6.8cm
Undamped	+/- 41.4cm	+/- 14.6cm
Damping ratio	2.92	2.15

The damping ratios for a crop of average density are presented in Table 5.6. The damping effect of the adjacent stems reduced the amplitude of the oscillations in the direction of the wind by 2/3, and at right angles to the wind by more than 1/2. These substantial effects will clearly moderate the effect of wind on stems. The damped movement of +/- 14.2 cm may be compared with the displacement of over 73cm found to be necessary to break whole stems in stem bending tests (Table 5.1). As the windspeeds during these tests were only moderate conditions would have to be extreme to give rise to sufficient displacement to result in breakage of the stems.

Stem base strain gauge

Towards the end of the project a method was developed for measuring the moment at the base of a wheat stem directly using a micro strain gauge. It was found that these strain gauges, about 2mm x 2mm, could be glued the base of the stem base and direct readings of the strain taken. Time did not permit this technique to be employed in the field.

The data gathered from the various stem bending tests and the morphological studies in this project would provide some of the necessary information for formulating a mathematical model of lodging. Techniques were developed such as those for analysing video images of stems undergoing wind loading and for attaching of miniature strain gauges to stem bases which could yield further useful data in the future. However it was not possible within this project to develop a sufficiently complete model of the stem to allow the resultant forces passed from the aerial stem system to the root soil system to be calculated.

The technique of Finite Element Analysis if applied to the aerial stem system would enable useful modelling to be carried out. The particular engineering software available in this project and which was useful when considering the root/soil system (Chapter 8) was, however, unable to model elastic material capable of large deflections like wheat stems and no further progress could be made in this direction.

Chapter 6

The soil/root interface

Anatomy and morphology of the root system

The structure of the basal area of the plant where the soil, shoot and stem meet is complex and subject to a wide variation in form. During germination primordia present in the embryo develop into the seminal roots. Although these are important during the early stages of crop growth it is unlikely that they perform any subsequent role in supporting the plant. As development of the crown and elongation of the stem proceeds adventitious roots formed at the crown become the principal root system of the plant.

The adventitious roots are fibrous and their orientation is outward and downward. For most of their length they are relatively homogeneous in form and in diameter and have little or no secondary thickening (Tomlinson, 1961). The roots have a greater diameter close to the crown than in their distal regions, tapering rapidly away from their origin. They have low branching ratios, often being unbranched for several centimetres, but do produce a dense proliferation of root hairs which infiltrate the surrounding soil, exuding secretions into it. The result of this is to bind soil to themselves forming a discrete and tightly matted rhizo-sheath. The roots at this level in the soil profile are quite rigid and can be considered to constitute the structurally supportive zone for the plant. The cell structure of the proximal regions of the roots also shows marked differences to that of the rest of the root. There is a degree of lignification of the outer layers of the cortex (Ennos, 1991), and the exodermis of roots in this area is far more persistent than in roots at other points of the soil profile. These roots do not seem to senesce along with the general senescence of the root system that occurs during grain filling and ripening (Percival, 1921) and new structural growth can occur after anthesis.

Growth of adventitious roots

The sequence of adventitious root growth and development has been described qualitatively in terms of the development of the rest of the plant by Klepper *at al*, (1984) and quantitatively in terms of thermal time, by Porter *et al* (1986). Adventitious roots are formed at the nodes of the stem. The majority of roots are produced at nodes 1 to 4, the internodes of which do not elongate and hence remain in and form the crown. Nodes 5, 6 and 7, whose internodes elongate slightly, are also capable of producing roots and sometimes produce aerial roots. By anthesis, after which lodging becomes a significant danger, the plant has already produced (with the possible exception of aerial roots) all the structurally important roots it is capable of producing. Each of the 7 nodes which are associated with the crown can have up to four adventitious roots, discounting aerial roots, so that up to 28 roots can be produced by a single un-tillered plant. Roots grow at between 5 and 20 mm per day so that after the first month of its growth the root will have grown out of the structurally supportive zone. The period of time required to attain its maximum structural strength is unknown. It is not known if all adventitious roots can become structurally adapted, though it seems likely that all have the potential to do so. This process could also be thigmomorphogenetically mediated.

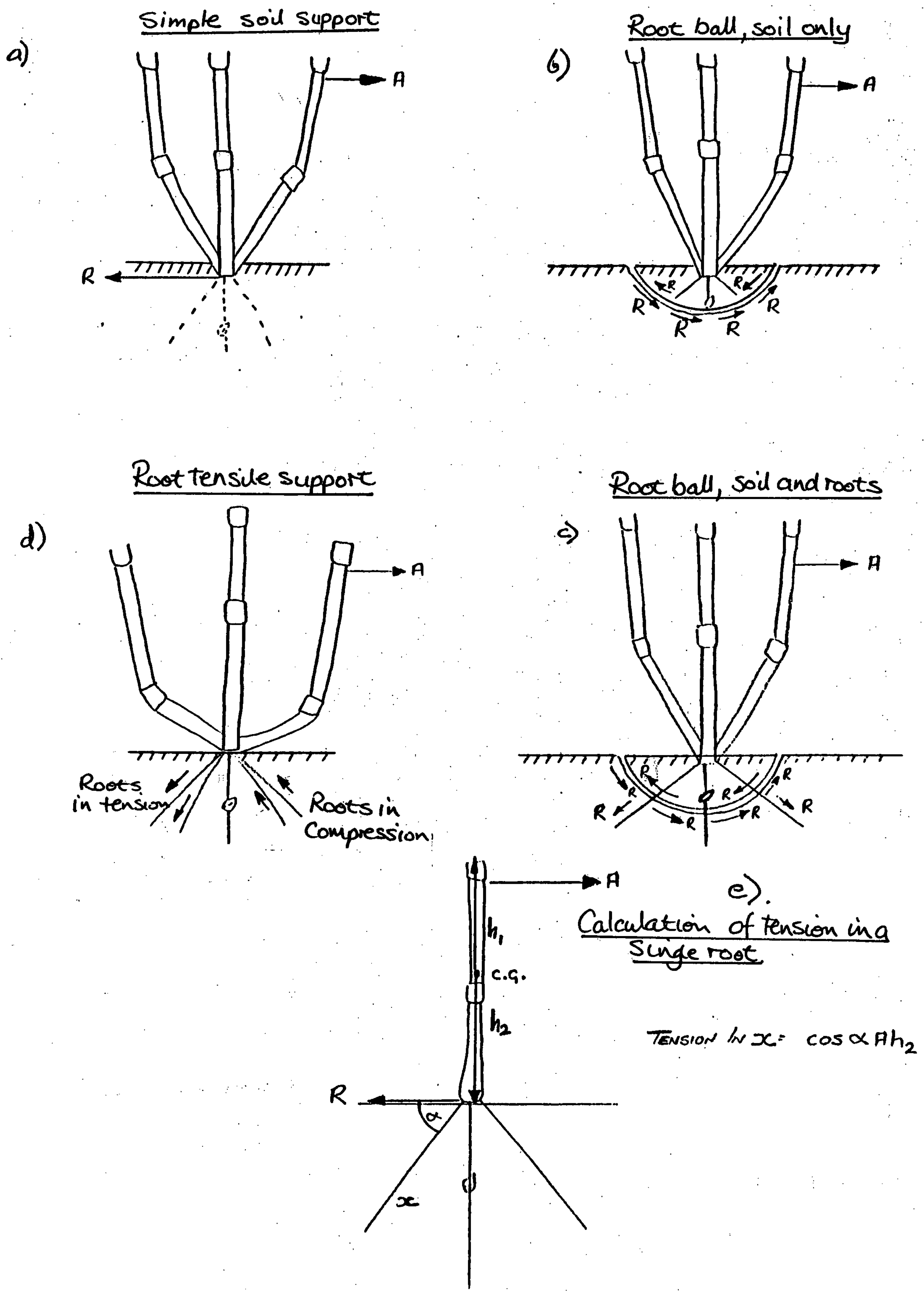
The spatial arrangement of roots, specifically the angle of attack of the roots to the perpendicular, has been shown to correlate with resistance to lodging (Pinthus, 1973). Due to the highly ordered nature of adventitious root production from the nodes it seems possible that the roots should exhibit a regular pattern around the crown.

Material properties of roots

Examination of the composite structure of wheat plant roots and comparison with other biological materials of known properties (Wainwright *et al.*, 1976) suggests that they should exhibit predominantly elastic behaviour. If stressed over a long period of time or through numerous stress strain cycles, it is probable that roots will exhibit considerable visco-elastic properties.

Very little work has been done on the material properties of cereal roots and that which has been done, predominantly on barley, has produced inconsistent results. Spahr (1960) reports

Figure 6.1


Simple soil support
a)
A
R
Root ball, soil only
b)
A
R
Root tensile support
d)
A
Roots in tension
Roots in Compression
Root ball, soil and roots
c)
A
R
e).
Calculation of tension in a Single root
A
h1
c.g.
h2
R
α
x
TENSION IN x = cos α A h2

experiments in which the lodging resistance of barley varieties could be correlated with the tensile strength of the roots. Although this is an encouraging result, Spahr makes no mention of other features of the root system. Breaking stresses of barley roots of between $9.9*10^5$ and $1.27*10^5$ g/cm^2 were measured by Neenan and Spenser-Smith (1975) and $7.6*10^5$ g/cm^2 by Waldron and Dakessian (1981), results which are slightly higher than our own figure for wheat roots of about between $4*10^4$ and $7*10^4$. The latter workers also calculated that the Young's Modulus and breaking stress of barley roots decreased with increasing diameter.

The breaking stresses of wheat roots were found by Neenan and Spenser-Smith (1975) to be similar to those found for barley roots. Young's Modulus of wheat roots was estimated by Dexter and Hewitt (1978) as 45 MN/m^2. They also recorded a non-linear response to successive loading of the roots which indicates that visco-elastic creep may have been happening. The same workers found similar values of Young's Modulus for the primary lateral roots of wheat plants. Nutritional factors were found to have a substantial effect on the elastic properties of the roots (Whiteley and Dexter, 1981). The most recent material properties work done on wheat roots, that of Ennos (1991), was carried out in order to substantiate a specific model. The stress required to bend a wheat root through 45 degrees was reported but the Young's Modulus was not derived so comparisons are not possible.

Soil structure and material properties

Soil can be considered a heterogeneous, polyphasic, particulate, disperse and porous composite structure (Hilliel, 1980), the complexity of which is such that any predictions of its behaviour are difficult. A number of classical mechanical models exist to describe the elastic behaviour of soil when subjected to compressive and shear stresses, for example that proposed by Coulomb as early as 1773, but these were formulated for use by civil engineers on problems specific to that discipline. These models only apply to compacted soils which are dissimilar in structure to the loosely packed soils commonly found in the top 15cm of agricultural soils, considered to be the critical zone for wheat plant support.

Graham (1985) proposed the use of critical state soil mechanics (Roscoe *et al*, 1958), to predict the mechanical behaviour of agricultural soils. This theory correlates the normal compressive stresses and the deviational shear stresses acting on soil with the resultant variations in pore space or volume. When combined with data concerning the variation in soil strength with increasing moisture content the theory allows predictions to be made concerning the magnitude of failure of a soil under stress and the mode of failure which occurs. He concluded that it is difficult to predict the exact mode of failure of a very wet agricultural soil as any one of a number of catastrophic failures will be brought about even by small stresses. Accounts of this theory with respect to agricultural soils can be found in Hettiaratchi and O'Callaghan (1980). This work highlights the weakness of the soil as a component part of the soil/root/stem complex, and led Graham to conclude that catastrophic soil failure is the major cause of lodging to the exclusion of plant factors.

Failure of the root/stem/soil system

Regardless of their views concerning the properties and behaviour of the aerial parts of the wheat plant, all workers recognise that when subjected to wind loading the above ground parts generate at the stem base a force acting parallel with the soil surface and a turning moment about it. If the plant is to maintain its equilibrium position then these forces must be opposed giving rise to resultant tensile, compressive and shear forces.

The exact parts of the soil/root/stem complex opposing the forces and the manner in which these forces are transmitted are major areas of uncertainty. Several theories for wheat plant support can be postulated.

Theory 1: Support of the plant mainly by the stem

If we consider the stem to extend below the soil surface, then it is possible that the plant could be supported by this structure in the manner of a flag pole. The force and moment induced by the aerial parts of the plant would be resisted by the soil preventing the reactionary movement of the subterranean section of the stem. This model would apply a substantial shearing force to the base of the stem (Figure 6.1a). During early development of wheat seedlings elongation the sub-crown internodes raises the apical meristem of the plant to within 1 to 2 cm of the surface. This region then becomes the crown. As the subterranean part of the stem is so short relative to the total height of the stem, it is unlikely to provide significant support to the stem.

It is quite common in wheat plants with a number of tillers for the internodes arising directly from the crown to lie parallel to the soil surface, the stem only achieving its vertical orientation at node two. If this is the case, these stems can resist the compressive forces generated by the aerial parts of the plant on the leeward side by leaning on the soil.

Theory 2: Support of the plant by a root ball

It possible to envisage the soil/root/stem complex as forming a compacted region within the soil, the "root ball", which remains attached to a plant if it is uprooted (Neenan and Spenser-Smith, 1975). This would have properties which differ greatly from the rest of the soil, and when the soil becomes wet, the force conveyed to it by the aerial parts of the plant would cause the impacted soil to move with respect to the bulk of the soil (Figure 6.1b).

This theory can be developed to take account of the various roles roots can play in the system. On one hand it is possible that the roots and their rhizosheath serve to hold together the root ball by compacting the soil (Barley and Greacen, 1967; Dexter, 1987). It is also possible that the roots bridge the gap between the "root-ball" and the rest of the soil, thus stabilising it. Furthermore, if the roots are serving to stabilise the system it is difficult to ascertain if the forces they are experiencing are tensile or shear forces.

While this theory is generally appealing to soil scientists, there are many problems, the main one being that the root ball is not a clear entity, the limits and properties of which can be defined and measured. Some estimate of its dimensions would be obtained by uprooting wheat plants by a vertical force, a technique shown to have some correlation with lodging resistance (Surganova, 1967) and measuring the size of the attached "root ball". This process, however, would have to be repeated for a large range of soil types, moisture contents and compactions.

Studies of tree stability often make reference to a notional entity called the "root ball" (Fraser and Gardiner, 1967). This factor and the maximum root spread diameter or diameter of the root plate are the main parameters in models of the tree root system (Henwood, 1973). Since the general architecture of the wheat root system is not dissimilar from that of trees (Fitter and Ennos, 1989), it seems possible that wheat plant stability could be modelled in the same way.

To adapt tree stability models for wheat it is necessary to assume that the root ball acts as a discrete footing and that this footing will rotate in a vertical plane under lateral loading. A system can be considered which has a stem with a root ball from which protrude two lateral roots which are antagonistic. This arrangement of wheat roots conforms to the natural system, in which roots develop in pairs on opposite sides of the stem (Figure 6.1c). Rotating the root ball has three effects. The soil on the leeward side of rotation experiences compression; the root on the leeward side will be put under tension, which, for small angles of bending can be considered to act parallel to the soil surface and the point of application of the force will be raised. Using this information, and assuming that the sum of the tension forces tend to exert a righting moment to counteract the turning moment caused by the weight of the aerial parts of the plant, total moments about the base of the plant are equal to zero.

Tillers can be added to the system by increasing the size of the root ball and the number of roots projecting from it whilst maintaining its general form. Lateral roots can be added at any depth and their three dimensional arrangement taken into account. However, as stated previously, it would be difficult to establish the actual size of the 'root ball', and as this would be one of the principal variables in the system this unknown makes the whole system difficult to model. Important aspects of this system would be the soil/soil interaction at the boundary of the variable root ball and the soil/root interactions both in shear and in tension. It may be concluded, therefore, that a model based on this theory would be complex to build and validate.

Theory 3: Support of the plant by roots in tension

Roots are very well designed to resist tensile deformations, and therefore it is likely that in the course of supporting the plant they are called upon to do so. The simplest possible case is that of a single stem with two roots and with the wind blowing parallel to the line of support of the roots (Figure 6.1d). In this instance one root is giving support in tension, whist the other is giving support in compression. If the roots can give little or no support under compression, which is a reasonable assumption, then all the support must be provided by the root under tension. Two basal internodes are assumed to be rigid or at least very stiff. We can regard the force as acting through the centroid of the two basal internodes and generating a reaction parallel the ground. For the structure to remain stable, the root must be capable of withstanding a component of that reaction which is equal to that in Equation 1.

(1) $Rcomp = \cos a\, fh_2$ where
f = force
h_2 = height to the centre of gravity
a = angle of root to soil surface
$Rcomp$ = reaction component in root

A simple three dimensional structural analysis of the wheat plant support structure was undertaken (see Chapter 8). Such structural analyses disregard the effect of materials, giving the answers in terms of the distribution of loads. The results showed that the forces generated by the aerial parts of the plant are divided unevenly between the roots and can lead to failure of the roots in tension. Previous workers had erroneously used the fact that wheat roots were relatively strong and the assumption that all roots shared the load equally, to discount the likelihood of root lodging (Neenan and Spenser-Smith, 1975).

However, like the previous theory, this root tensile theory also fails to take into account the interaction between the plants and the soil. Since the roots are quite strong relative to the soil, especially when the soil is wet, it is probable that the support system would fail at the root/soil interface. Graham (1985) makes reference to this form of loss of support stating that tension in the roots would give rise to tensile forces in the soil. Since soils and especially wet soils are very poor at resisting tensile forces, this would lead to a breakdown in soil structure and the consequent pulling free of the root from the soil.

Ennos (1990) proposed a model for the uprooting force of an unbranched leek seedling root which he validated by experimentation. He considered a root of constant radius which behaves perfectly elastically in tension, embedded in soil which is perfectly rigid and perfectly elastic with infinitely high shear stiffness. If such a root is placed in tension its uppermost part will stretch and the deformation of the root will result in shear stresses between the root material and the soil in this zone caused by friction between the root and the soil or within the soil. Hence tension in the root is resisted in part by the soil. The greater the tension applied to the root, the greater the area of root/soil interface which must be overcome in order to pull the root from the soil and the greater the length of the root which will be stressed. Failure will occur by the breakdown of the soil/root bond or by the breakdown of the soil structure itself.

The rate at which tension is removed from the root through its interaction with the soil will be proportional to the surface area of the root and the shear strength of the soil at the soil/root interface. Therefore, tension within the root falls with its depth in the soil (x) according to Equation 2, and the force, F, required to break the root/soil bond to a depth , x, is given by Equation 3. A root of given length which does not break will pull free from the soil when subjected to a force defined in Equation 4.

(2) $dt/dx = 2\,Pi\,R\,a\,r$ rate of fall of tension

(3) $F = 2\,Pi\,R\,a\,r\,x$ tension at depth x

(4) $Fp = 2\,Pi\,R\,a\,r\,L$ force to pull out root of length L

(5) $Fb = Pi\,R^2\,S$ force to break root of strength S

(6) $Fp > Fb$ i.e. $2Pi\,R\,a\,r\,L > Pi\,R^2\,S$
if true, root will pull out

Where:
F = force
h2 = height to centroid
t = tension
x = depth in soil
a = relative strength of root soil bond
r = soil strength
Fb = force to break roots
Fp = force to pull roots from soil
S = breaking stress of roots
R = radius of root
L = length

(Ennos, 1990)

If the breaking stress of the root at depth x is less than the root/soil bond strength then the root will break at that depth. The breaking strength of the root will be given by the Equation 5. When put in increasing tension roots will break if Equation 6 is true, otherwise they will pull free from the soil.

For the purposes of support roots can be assumed to be of infinite length, so that they will always break rather than pull free. The point at which roots will break is given by Equation 7, which is derived by Equation 5 over Equation 4.

(7) $Lcrit = \frac{S\,R}{2\,at}$ Where Lcrit = critical length

This model is extremely useful in enhancing our understanding of the behaviour of roots under tension. In comparison with the leek roots being considered by Ennos, however, cereal roots show a marked tapering and reduction in breaking stress over the first 12cm (Table 7.1). This will significantly reduce the critical length and the expected pattern of root failure. The presence of branch roots is likely to be a more difficult problem to deal with using this model.

The root/soil complex as a fibre reinforced matrix

In carrying out experiments on pulling wheat roots free from soils of different types and moisture contents (Chapter 7) it was noted that the extraction curve for wheat roots had a regular form (Figure 7.4), although it was dissimilar to that described by Ennos. The extraction curve of the wheat roots corresponded more closely to the load displacement curve of a fibre reinforced composite (Ashby and Jones, 1986). The stress/strain curve is linear until the matrix yields. From there on, most of the extra load is carried by the fibres which continue to stretch elastically until they fracture. The stress gradually drops to the yield strength of the matrix in stages as the fibres break. When the matrix fractures the composite fails completely. This behaviour should not be surprising as wheat roots embedded in soil clearly fit the definition of a fibrous composite material.

The behaviour of a composite of this type under tensile stress can be described mathematically. The elastic modulus of a fibrous composite, when loaded along the fibre direction, as is the case for adventitious roots in tension in soil, is a linear combination of that of the fibre Ef, and the matrix Em (Equation 8) (Ashby and Jones, 1986).

(8) $Epll = Vf\,Ef + (1\text{-}Vf)Em$

(9) $Erta = \{Vf/Ef + (1\text{-}Vf)/Em\}^{-1}$

Where
Epll = Modulus of composite with fibres parallel to the load
Erta = Modulus of composite with fibres at right angles to direction of the load
Vf = Volume fraction of fibres
Em = Modulus of the matrix
Ef = Modulus of the fibre

When loaded at right angles to the fibre direction, as in the secondary accruals, the modulus is given by Equation 9. This is much less than when loaded along the fibre direction but still greater than that of the soil alone.

In the case of resisting forces generated by the aerial parts of the plant it is the breaking stress which matters. Where this occurs at the peak, the fibres are just on the point of breaking and the matrix has yielded, so the stress is given by the yield strength of the matrix and the fracture strength of the fibres, combined using a rule of mixtures (Equation 10). There is a critical length for fibres above which further length contributes little to strength. For this reason wheat roots need only be structurally adapted over a relatively short part of their length as indeed they are.

(10) Strengths = Vf* Fracture strength of the fibre + (1-Vf)* Yield strength of matrix

(Ashby and Jones, 1986)

The above theory is in a very basic form and would only apply to compacted soils. The discipline of fibre reinforced soils is, however, rapidly expanding and it would be possible to incorporate matrix behaviour as predicted by critical state theory with further research.

It is possible to ascertain the yield and fracture strength of soils and of roots, and to obtain the percent fraction of roots in soil at various points in the soil profile. The fraction of root material in soil profiles could alternatively be predicted from other models (Bragg *et al*, 1984; Andrews 1987). The above theory could therefore form the basis for a model of lodging in which the forces generated by the aerial parts of the plant are resisted by a fibrous composite. In a model of this sort, the specific form of the crown and the root system would be largely irrelevant. This concept has considerable possibilities for the future as it deals with measurable factors, and has implications for the manipulation of soil properties to reduce lodging.

Chapter 7

Experimental work on the root/soil system

The experimental work on the root system can be divided into three areas in which firstly, the material properties of the roots were studied through tensile tests carried out on the Instron, secondly the mechanical resistance of roots to being pulled from soil was studied using wheat grown in pots and thirdly the nature and properties of root systems of wheat in the field were studied through the sampling of plots from the 1990 seed-rate experiment both before and after lodging. In a final stage data from these studies were incorporated into a model of the wheat support system based on Finite Element Analysis which is discussed in Chapter 8.

Root material properties

Failure in roots is more likely to occur as a result of tensile rather than compression or shear forces. Experiments were therefore carried out to investigate the tensile properties of wheat roots. Initially work was done to establish the technique using 60 root samples from a field area of wheat. The Instron was set to apply the necessary load over a period of 1 second, comparable to the natural freqency of a wheat stem. The roots were gripped in miniature pin vice chucks.

In subsequent work comparisons were made of the properties of roots from high and low N plots from the 1989 experiment. Half metre rows of plants were sampled from high and low N treatments without PGR in each of the three blocks. One randomly selected undamaged adventitious root from each of 10 plants was used to determine the root taper by measurement of the diameter at 1cm intervals along the first 20cm of root length. This was then divided into 3 sequential 4cm lengths and the tensile properties of each segment determined using the Instron testing rig.

The roots tapered markedly over the 12cm and this was associated with a significant difference in the breaking load which fell from an average of 700g for first the 4cm to 200g for the 8cm to 12cm section (Table 7.1). The traces from the three sections of a typical root are shown in Figure 7.1. The Peak Displacement and the Strain were very consistent and showed no tendency to change along the length of the roots or to be influenced by the level of nitrogen. As a result breaking load was significantly correlated with area over all the 60 samples which were tested, breaking load (g) = area (sq mm)* 400 (Figure 7.2). As a result the Breaking Stress did not change significantly along the length of the roots, although it did appear to be lower at the low N than at the higher N rate. These results would suggest that the inherent material properties of the root do not change along its length and that the main characteristic which will be important with regard to lodging will be the relationship between root diameter (area) and breaking load.

There was some indication that nitrogen did have an effect on the root properties, resulting in a higher breaking stress and a higher Modulus of Elasticity which will tend to increase resistance to lodging in high N plots. The observed higher instances of lodging in such plots must therefore be due to the effects of N on other lodging related characteristics such as above ground biomass or plant height.

The relatively consistent material properties of wheat roots was confirmed in subsequent experimental work carried out in both the 1989 and 1990 seasons in which roots were sampled from plots representing the treatments:- i) Ethephon with mepiquat chloride vs untreated; ii) chlormequat vs untreated, iii) low and high seed-rates (Table 7.2). The samples were prepared in a similar way to that described above.

Seed-rate was the only factor to have a significant effect on the root diameter with significantly thinner roots being produced at the high seed-rate. The breaking load at the higher seed-rate appeared to be proportionately lower, but the difference did not quite reach statistical significance. Although the growth regulators used in this experiment promote lodging resistance they do not affect the material properties of the roots themselves so their effects must be mediated in some other way such as the alteration of stem morphology, root numbers or root arrangement.

Table 7.1

The material properties of root sections different distances from the crown at two rates of applied nitrogen, 1989

	Root Diameter (mm)	Breaking Load (g)	Breaking Displ. (mm)	Breaking Stress (g/mm^2)	Breaking Strain	Modulus
150 kgN/ha						
0 to 4cm	1.27	632	6.10	582	0.30	20.41
4 to 8cm	0.81	309	5.96	455	0.30	15.61
8 to 12cm	0.48	184	5.51	407	0.28	14.62
250 kgN/ha						
0 to 4cm	1.43	771	5.03	595	0.25	24.69
4 to 8cm	0.73	379	6.10	651	0.30	21.10
8 to 12cm	0.39	228	6.24	692	0.32	22.39
sig. N	NS	NS	NS	*	NS	***
Root section	*	*	NS	NS	NS	*

Table 7.2

Effects of various treatments on root mechanical properties, 1990

	Root Diameter (mm)	Breaking Load (g)	Breaking Displacemt (mm)	Breaking Stress (g/mm^2)	Breaking Strain	Modulus
Seed-rate						
Hornet 100	1.10 *	552	4.07	681	0.20	33.6
Hornet 800	1.00	436	3.34	560	0.17	34.9
Ethephon PGR						
Terpal	1.13	553	3.13	566	0.16	35.4
Control	1.07	508	3.58	563	0.18	31.5
Chlormequat PGR						
CCC	1.17	494	3.79	423	0.19	25.5
Control	1.17	495	4.62	479	0.23	22.3

* Significant at 5% level.

Soil/root cohesion

As it was impractical to consider trying to measure the support provided by individual roots to the plant in a field situation a method was developed to examine soil/root cohesion of undisturbed wheat roots in plants grown in pots. Wheat plants were grown in pots in which had been embedded four soil filled mesh tubes of 2.5 cm diameter and 7.5 cm length arranged in a pyramid at an angle of about 40° (Figure 7.4). At maturity the mesh tubes were retrieved and the roots associated with each tube were then clipped down to within 1cm of the soil. Each tube was inserted into a wooden holder and clamped to the base of the Instron. The root to be pulled was gripped by a miniature chuck held in the upper arm of the Instron. After pulling the root was examined and a note taken if it had broken or cored for part of its length. Coring was when the inner conductive tissues or stele of the root had

Figure 7.1

Tensile Properties of Wheat root sections

of typical sample

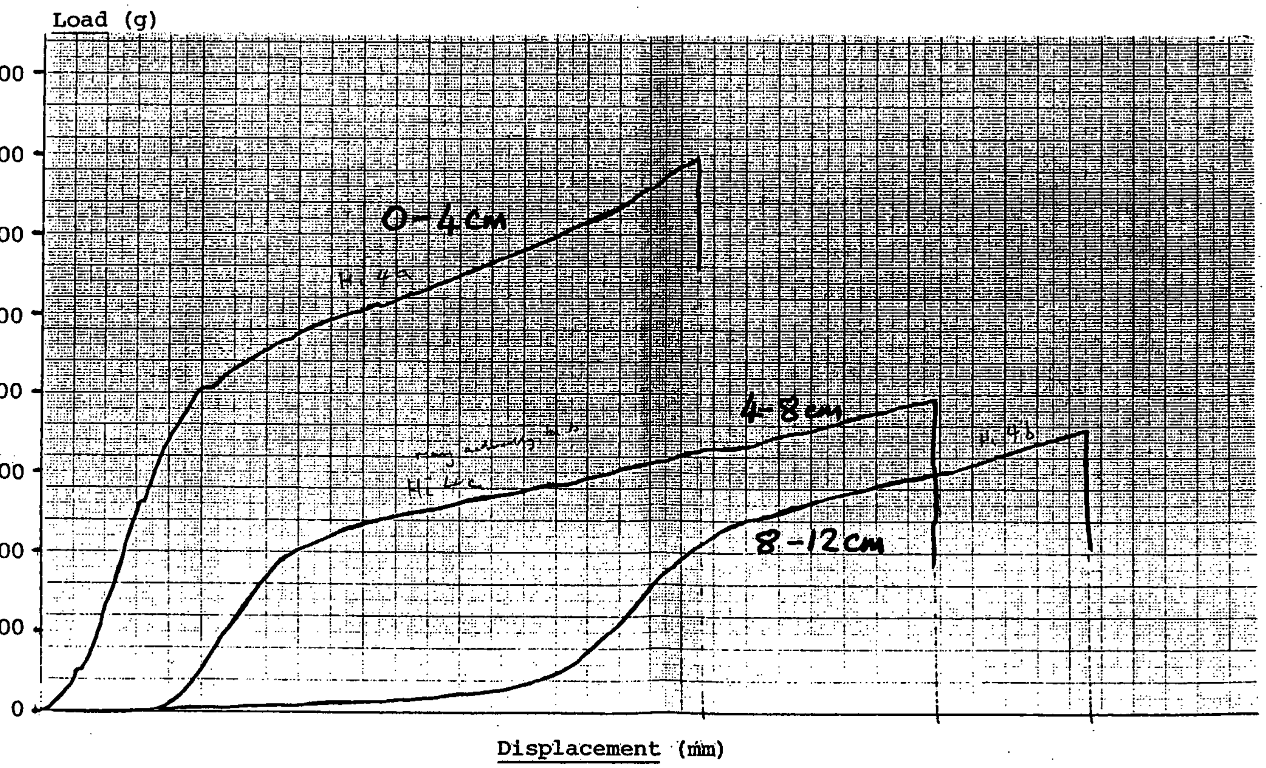


Figure 7.2
Wheat root properties

Breaking load vs X sectional area

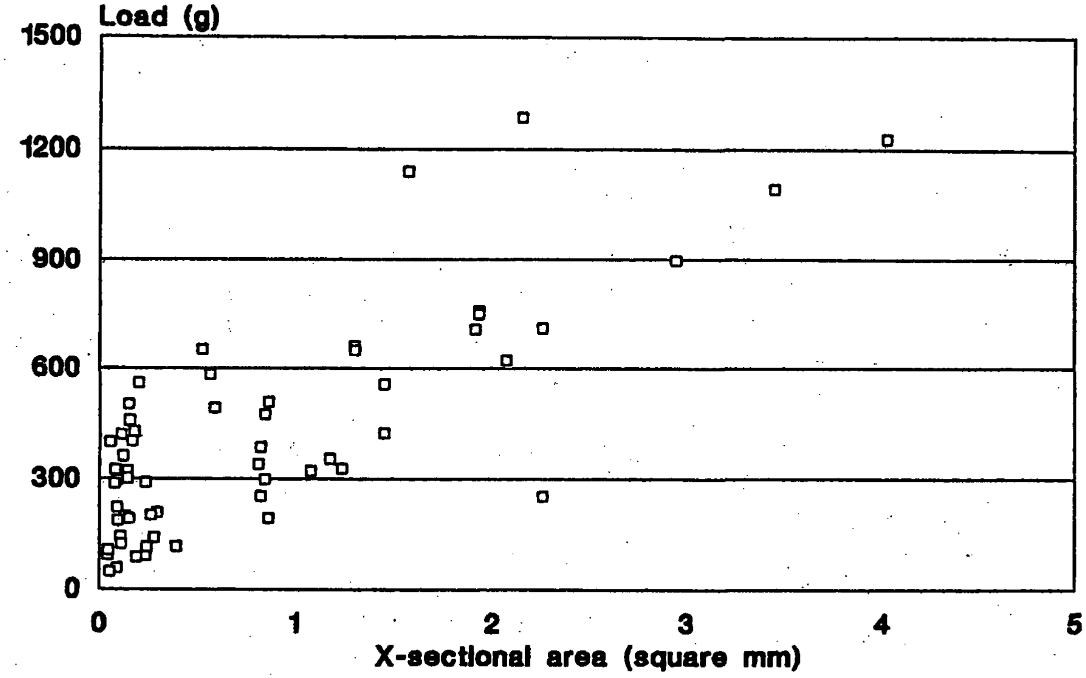
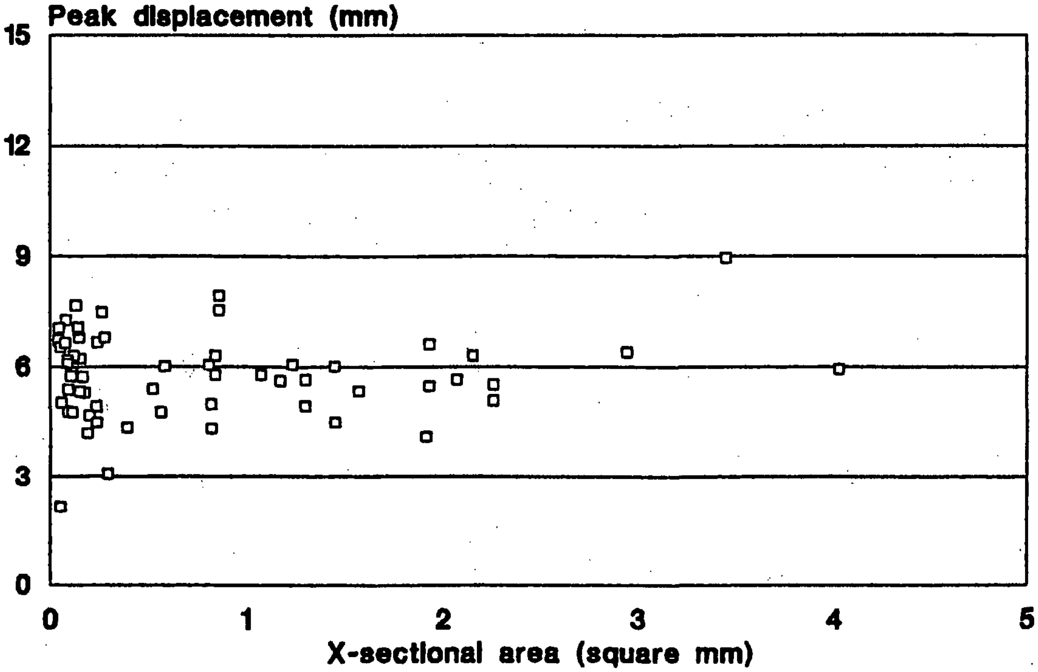


Figure 7.3
Wheat root properties

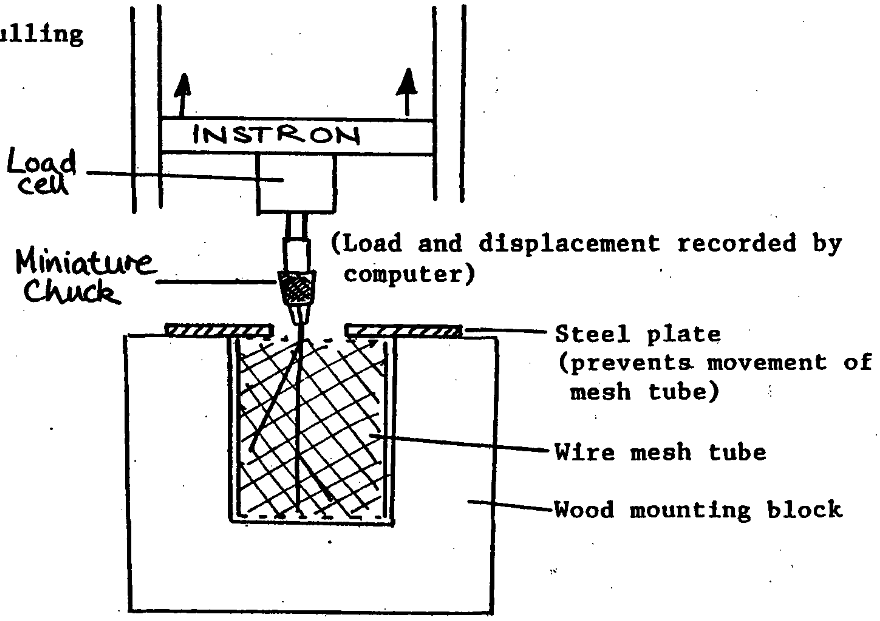
Peak displacement vs X sectional area



ROOT PULLING EXPERIMENT

Figure 7.4

Root pulling



Growing material for root pulling experiment

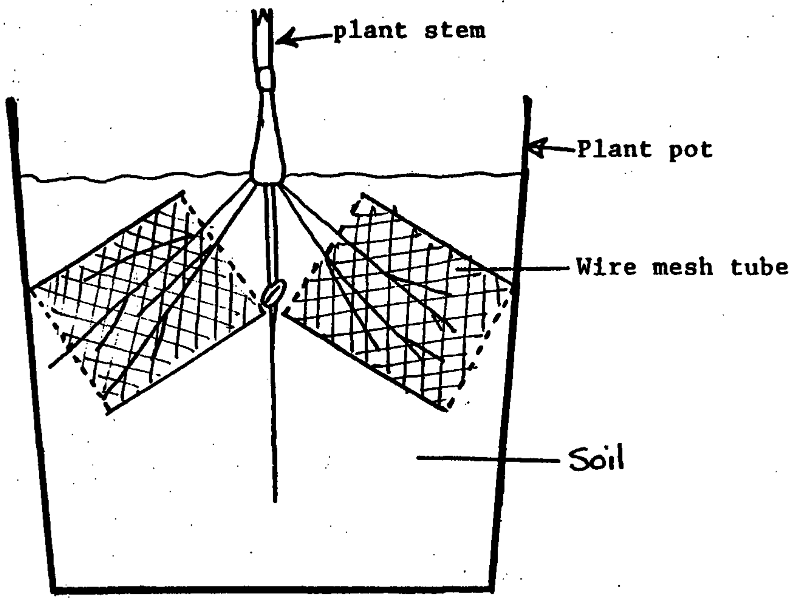
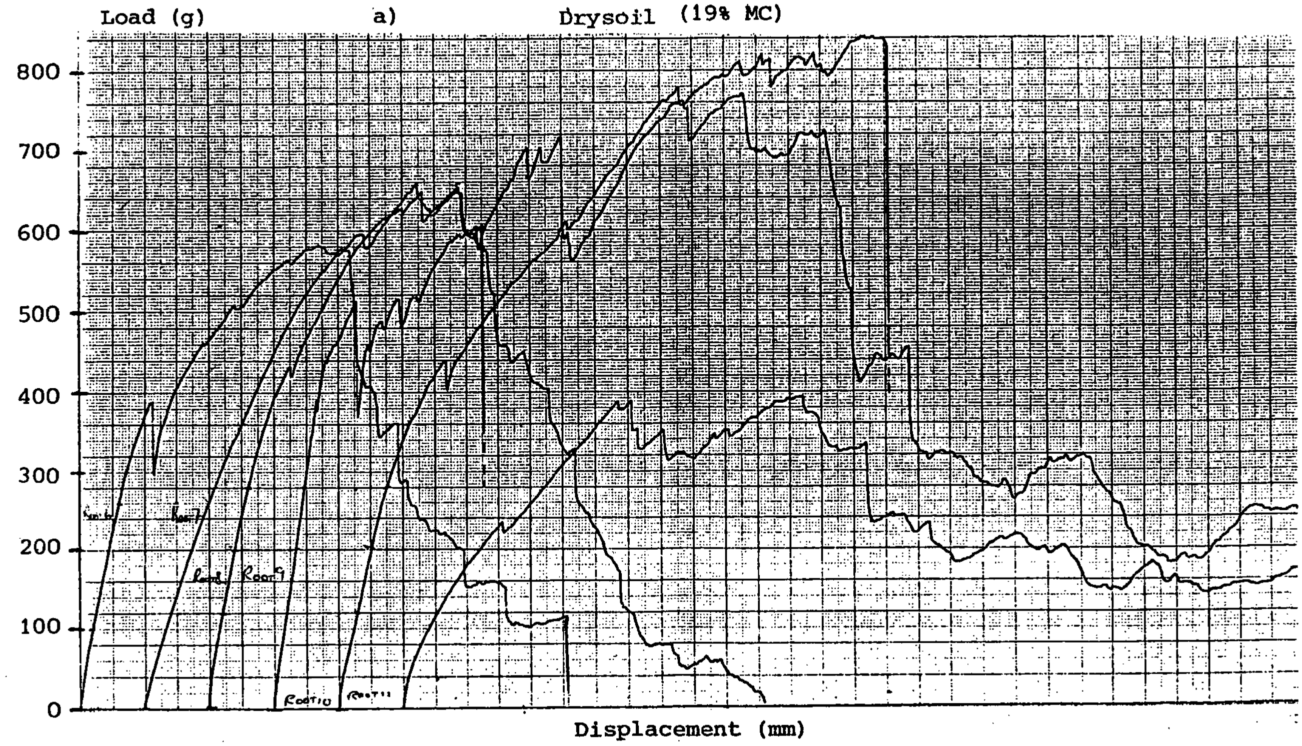


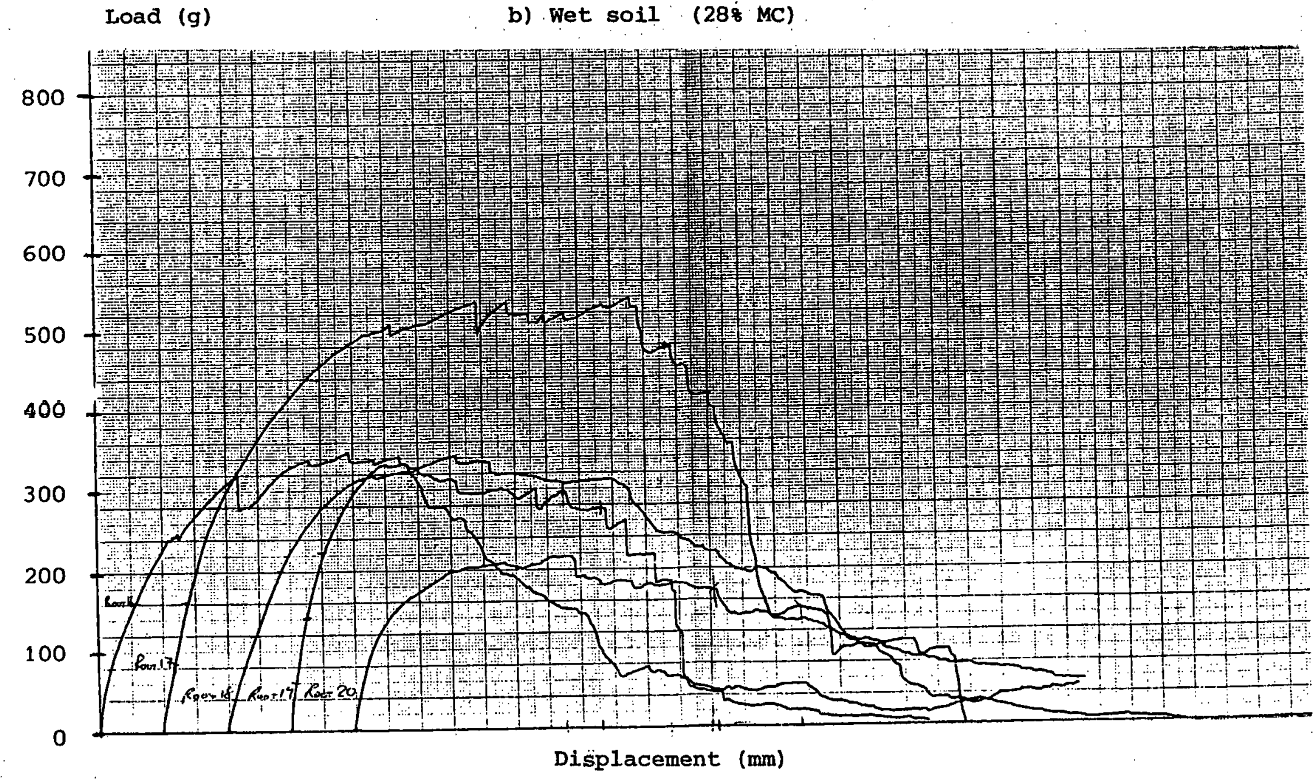
Figure 7.5

Typical Load vs displacements for root pulling from wet and dry soils

a) Drysoil (19% MC)



b) Wet soil (28% MC)



pulled free leaving the outer layers of the root in the soil. This could happen along all or part of the length of the root. The soil in each tube was oven dried to determine the moisture content at the time of pulling.

Root pulling experiments were carried out in both 1989 and 1990 used soil gathered from two sites with differing soil types as shown in Table 7.3. The soil was sieved to remove stones and the mesh tubes filled with the soil to a density similar to that found in the field.

Table 7.3

Details of the soils used in the root pulling experiments

	Soil 1	Soil 2
Source	Maginnis Hill	Kilpatricks
Type	Sandy clay loam	Sandy loam
Sand %	48	65
Silt %	30	20
Clay %	21	15
Organic matter %	5.94	5.32
pH	6.0	6.34

When ready for testing the pots were left un-watered for 48 hours. The above ground parts of the plants were removed and the mesh tubes exhumed. The effects of soil moisture content on the force required to dislodge the roots was examined by subjecting the tubes to various watering regimes in order to give a range of soil moisture contents. In the 1989 experiment 3 moisture regimes were tested as outlined below.

i) Dry soil. No water was added to the soil for 48h.
ii) 2/3 field capacity. 200ml of water was added to the tube. This amount was approximately 2/3 that required to achieve field capacity.
iii) Field capacity. Water was added slowly to each tube until it began to drain through the bottom of the tube.

In 1990 two moisture regimes were tested representing the dry and field capacity soils.

Examples of the traces of root pulling from wet and dry soils are shown in Figure 7.5. The roots tended to pull irregularly from the dry soil, the load reaching several peaks both before and after the maximum. In some cases these peaks could be associated with side roots which could be seen pulling into the tube. The roots would either pull right through the soil of the tube, break cleanly in the soil or the sheath of the root would break at some point so that only the core of the root would then pull free. The results given in Tables 7.4 and 7.5 summarise the differences in the main characteristics which were observed.

In neither experiment were there significant differences between the two soil types in terms of the peak load. However, when wet both soils showed significant reductions in the peak load. The trace (Figure 7.5b) also shows that the roots pulled more smoothly from the wet soil. The loads for dry soil averaged 480g in 1989 and 560g in 1990, with figures of up to 1kg being recorded, while at field capacity the peak loads were 330g and 360g respectively. A higher proportion of the roots from the dry soils cored on pulling while in the wet tubes more roots broke. In neither experiment did the length of the roots follow the expected pattern as the roots from dry soil tended to be either longer or pull right through the soil, which occurred in 1990 in a higher proportion of roots. However, there were significant differences in the positions of the remaining branches which were closer to the top of the root after pulling from wet soil.

The results from these experiments show a clear lowering of the root/soil cohesion when the soil approaches field capacity. The pulling force required for dry soils of 500g or greater would be similar to the breaking load for the first 4cm of root length, while the pulling force of 300g to 400g for wet soil would equate with the breaking load for the 4cm to 8cm section of root. The results also indicate that the root branches within the first 6cm or 7cm may also play a role in supporting the plant.

Table 7.4

Root pulling experiment, 1989

Effects of soil type and moisture content on root pulling characteristics

	Soil 1	Soil 2		Normal	Field Capacity	200cc	
Soil moisture (%)	25.88	18.46	***	17.78	25.62	23.10	**
*							
Root diameter (mm)	1.06	1.25	*	1.16	1.19	1.10	NS
Root length (cm)	59.8	53.2	NS	55.5	59.6	54.4	NS
Sheath length (cm)	50.7	41.4	*	54.5	41.3	42.4	*
Cored roots (%)	41	50		44	18	38	*
Broken roots (%)	48	48		54	72	62	
Intact roots (%)	11	2		2	10	0	
Peak load (g)	400	331	NS	480	364	254	**
*							
Peak displ. (mm)	8.36	6.04	*	7.75	7.52	6.32	NS
<u>Distance to root branches (cm)</u>							
1st side root	3.58	4.13	NS	4.59	3.96	2.94	*
2nd side root	5.31	5.37	NS	6.74	4.91	4.37	**
Elastic displacement	2.5	2.5	NS	2.5	2.0	2.9	NS

Table 7.5

Root pulling experiment, 1990

The effect of soil type and moisture content on root pulling measurements

	Soil Moisture %	Root Diameter mm	Breaking Load g	Breaking Displ mm	Root Length mm	Root Branches
Soil 1	20.45	0.90	481	6.86	61.8	18.7
Soil 2	21.60	0.74	416	7.69	67.6	17.6
	NS	NS	NS	NS	NS	NS
High moisture	26.1	0.68	338	6.23	54.4	13.7
Low moisture	15.9	0.86	559	8.32	49.4	22.5
	***	NS	***	*	*	*

Root systems of wheat in the field

Support given by the root system to the plant depends on the number, size and distribution of the roots. The 1990 variety/seed-rate experiment was sampled to collect data on these characteristics for unlodged plots at the 50, 200 and 400 seed-rates. When severe lodging occurred in the experiment the opportunity was taken to compare the characteristics of lodged and unlodged plots. This was carried out on two occasions, firstly with the 1600 and the 800 seed-rate plots, and secondly with the 800 and 400 seed-rate plots.

Table 7.6
Plant characteristics at 50, 200 and 400 seeds/m2 on 23-25 June 1990

	Seeds per square metre						
	50		200		400		
	pulled	dug	pulled	dug	pulled	dug	
Plants/m^2	41.7		151.2		260.2		***
Stems/m^2	279		285		335		NS
Stems/plant	6.65		1.89		1.29		***
Fresh weight kg/m^2	4.61		5.75		6.39		
Numbers of roots							
Total/m^2	2848	3152	3520	3856	6000	5952	***
Total/plant	67.9	75.2	22.6	25.5	23.1	22.9	***
Total/stem	11.46	11.78	12.61	14.78	18.46	20.18	***
Weights of roots (g)							
Single root	0.072	0.072	0.034	0.047	0.052	0.040	***
Total/m^2	204.8	227.2	120.0	179.2	312.0	236.8	**
Total/plant	4.87	5.41	0.80	1.19	1.20	1.16	**
Total/stem	0.65	0.78	0.46	0.61	0.93	0.93	**

Protocol for crop sampling

Two 0.25 m^{-2} quadrats were randomly positioned in the plot, the positions of each plant within the quadrats mapped and the number of stems per plant were counted. From one quadrat each plant was dug carefully from the soil and the soil washed from the roots. In the other quadrat the plants were tugged vertically and the maximum distance from the plant at which the soil was disturbed noted. The plants were then pulled free from the soil, the roots washed, and the lengths of the longest and the shortest roots were measured.

For each quadrat the number of thickened roots and the total number of roots were counted. The ten largest roots were selected and weighed and their diameters at 4 cm from the crown measured. The total root mass and the total above ground biomass were weighed and the dry matters determined.

Plants at the lowest seed-rate tillered out sufficiently to produce almost as many stems as the seed-rate four times greater (Table 7.6). The fresh weight of individual stems was similar at seed-rates up to 400, but declined at 800 and 1600 seeds per square metre (Table 7.7). The total above ground fresh weight increased with seed-rates up to 400 per square metre, but tended to decline with further increases in seed-rate. The number of roots per square metre increased with the seed-rate but the number of roots per plant tended to decline. Surprisingly, the number of roots per stem increased significantly as the seed-rate increased from 50 to 400 seeds per square metre whereas from the 400 to the 1600 seed-rates there was a decline. However, at the 50 seed-rate the individual roots were nearly twice the dry weight than at the higher seed-rates. The smaller number of roots at the 50 seed-rate was supporting an above ground fresh weight of only 4.6kg compared with 6.4kg at the 400 seed-rate.

The differences between the root systems of the plants which had been dug up as opposed to pulled up were generally not significant and showed contradictory trends. At the 50 and 200 seed-rates pulling up tended to result in lower weights of roots than digging while at the 400 seed-rate the opposite was found.

Comparison of lodged and unlodged plots

One 0.25 m^{-2} quadrat was randomly positioned in the plot, the plants were pulled free from the soil, the soil shaken off and the plants weighed. The numbers of stems and ears were counted and a sub-sample of ten main stems was collected. For each main stem the length of internodes 1 to 6 from the top of the plant, the diameter of internode 6, the number of thickened roots, the total number of roots, the length of the longest and shortest roots and the fresh weight of the roots were recorded.

On 10th June the lodged 1600 seed-rate had lower fresh weights per square metre and per stem, slightly shorter stems and thinner basal internodes than the unlodged 800 seed-rate. The number of roots per stem, root lengths and dry weight per root were also lower in the lodged 1600 seed-rate than in the unlodged 800 seed-rate. On 10th July the comparison between the lodged 800 and unlodged 400 seed-rates similar. On an individual stem basis fresh weight in the lodged plots was half of that in the unlodged plots. The number, length and weight of roots per stem showed a much smaller proportional reduction in the lodged than in the unlodged plots except for dry weight on 10th June.

These results do not indicate that any one characteristic led to failure in the system. The lodged plots in both cases was carried less weight above ground both on a per unit area and per stem basis than the unlodged; the plants were not consistently taller and in proportion to the fresh weight being carried above ground the lodged plots had as many and as strong roots as the unlodged. Other characteristics which were not measured could also have been of importance, such as the weight of water on the crop or the elasticity of the stems. The model of the whole system would help to identify how all the factors contributed to the occurrence of lodging.

Table 7.7

Comparison of lodged and standing plots, 1990

Sampling date	10th June			10th July		
Seed-rate	1600 Lodged	800 Standing	SE mean	800 Lodged	400 Standing	SE mean
Fresh weight kg/m^2	4.89	6.55	0.34	5.72	36.10	0.251
Stems/m^2	1232.8	735.2	50.68	733.6	361.2	41.84
Ears/m^2	867.2	541.2	48.32	547.2	250.0	36.68
Weight per stem (g)	3.97	8.91		7.80	16.88	
<u>Length of internodes (mm)</u>						
Top	159.7	195.7	3.79	299.2	265.9	2.07
2nd	197.4	204.5	1.62	252.0	239.1	3.85
3rd	150.1	154.4	1.39	183.0	169.1	3.19
4th	110.8	109.3	0.71	130.8	119.9	1.55
5th	99.3	92.9	0.80	124.4	121.3	1.54
6th	33.5	38.8	1.57	42.4	35.9	1.32
Total	750.8	795.6		951.2	1031.8	
Internode 6						
Diameter (mm)	2.71	3.35	0.68	3.44	3.74	.012
<u>Roots per stem</u>						
Number	12.84	15.59	0.269	22.57	24.82	0.558
Longest (mm)	39.5	52.9	2.13	53.85	58.11	0.718
Shortest (mm)	9.97	10.03	0.407	10.41	10.41	0.028
Dry Weight (g)	0.146	0.395	0.022	0.414	0.654	0.0328

Chapter 8

3-Dimensional modelling of root tensions

Resolving root tensions

Having determined the number of roots per stem present in the wheat at a range of seed-rates, and assuming that the roots are distributed uniformly round the stem and at an angle of 40° to the horizontal it is possible to use an applied mechanics three-dimensional modelling program (Finite element analysis) to resolve the forces resulting in each root from a horizontal force applied at the soil surface. This was done using the 'Spaceframe' software of QSE Ltd. The position of the crown of the plant and of each root was plotted on a three-dimensional lattice and the properties of each root or 'member' were specified.

A simple root tension model

In the first model a relatively simple root arrangement was envisaged in which all roots were attached to the crown at one point. The effects of varying the number of the roots, and of the failure of specific roots was examined. A plan view of the basic model is given in Figures 8.1 and 8.2.

The following assumptions were made in constructing the model.

i) The roots are straight members all attached to the stem at the same point.
ii) All the roots have the same mechanical properties.
iii) The roots offer insignificant resistance in compression.
iv) The roots at an angle of less than 90° to the direction of the load are in compression.
v) The roots at an angle greater than 90° to the direction of the load are in tension.
vi) The resultant force acting on the root system is a steady horizontal force at the soil surface acting in one direction.

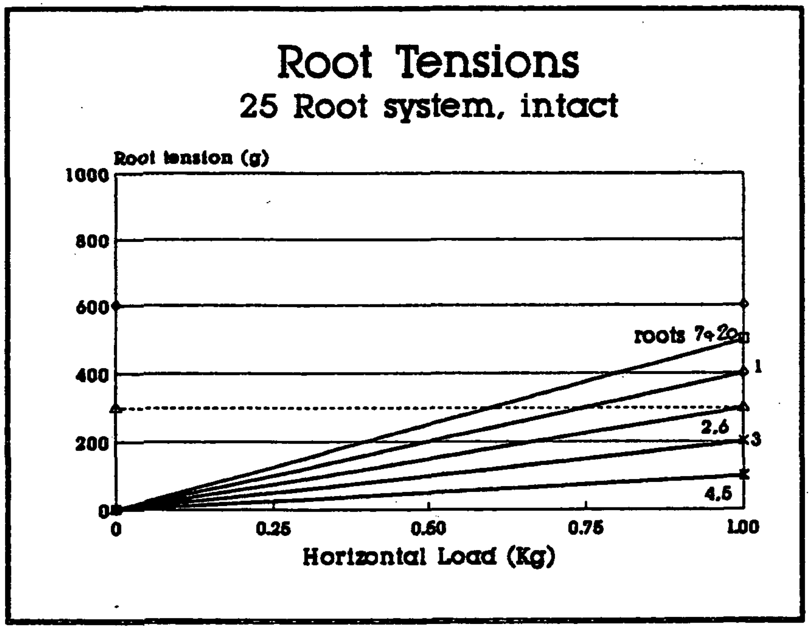
The tensions present in the roots were resolved for the three highest seed-rates in which substantial lodging had been observed. The number of roots per stem was taken as being 13, 16 and 25 for the 1600, 800 and 400 seed-rates respectively. In order to simulate the effect of the start of lodging the tensions were also resolved assuming that the two roots bearing the greatest tension had given way.

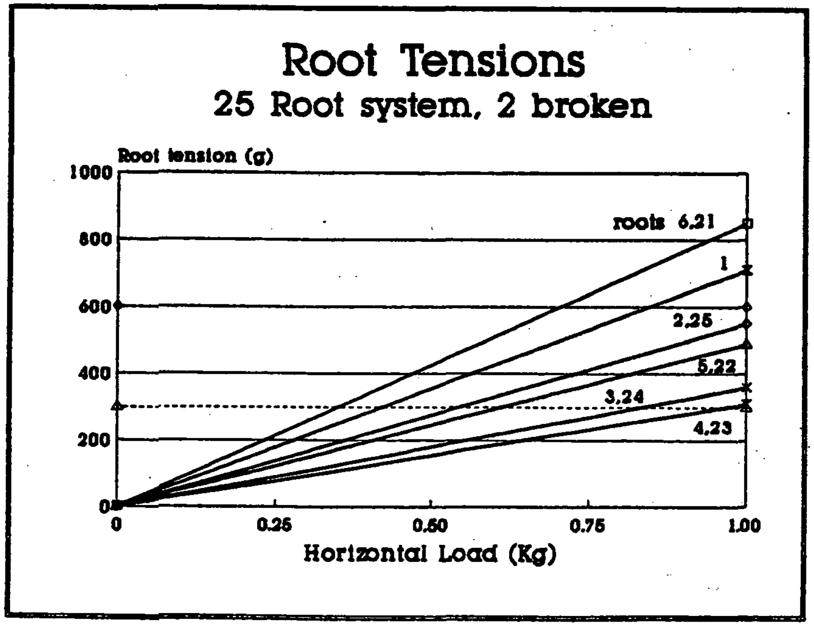
The results of this modelling, presented in Figures 8.3 to 8.8, are given for horizontal forces up to 1kg acting at the soil surface. From the root pulling experiments it was found that to pull an individual root from dry soil required a force of about 600g and from wet soil about 300g. Horizontal lines have been placed on each Figure to indicate these tensions.

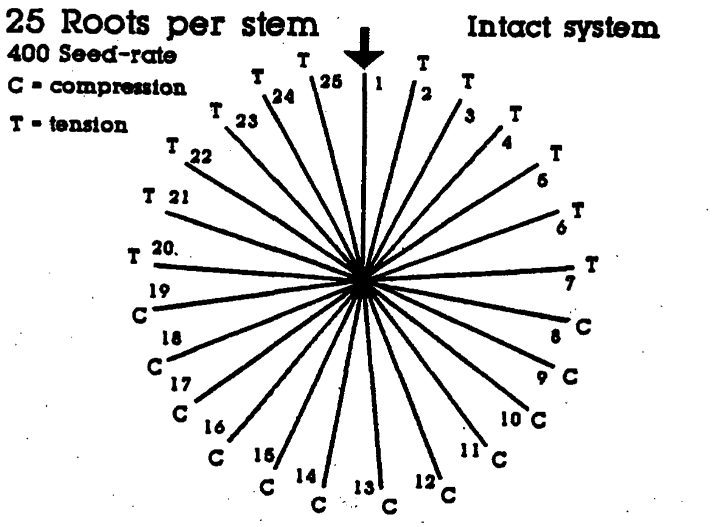
At all three seed-rates the tensions present in the roots varied widely depending upon their position. The roots in greatest tension were invariably those closest to 90° from the direction of the load. Those close to 180° also carried a high tension while the intermediate roots had lower tensions. At a loading of 1kg the greatest tension in any root of the intact root system fell from 800g with 13 roots to 500g with 25 roots. However, where 2 roots had given way the increase in tension in the system with fewer roots was much greater, rising to 1800g for the 13 roots system and to 850g in the 25 roots system.

It has already been shown that each lodging event was associated with a rainfall period so that we can consider the likelihood of roots pulling from a wet soil, requiring a root tension of about 300g. The process of lodging involving failure of the roots in tension can be explored by examining events in the simulated 1600 and 400 seed-rate plots. From the Figures at the highest seed-rate (13 roots system) a horizontal force of 380g at the soil surface would have resulted in the first pair of roots giving way. Once the first roots had given way the same force of 380g would place all the remaining roots under a tension of greater than 300g so that the whole root system would fail very rapidly.

In the 400 seed-rate plots in wet soil conditions the first roots would give way under a horizontal loading of 600g. On the failure of these first roots five further roots would be likely to become


Root Tensions
25 Root system, intact
Root tension (g)
1000
800
600
400
200
0
roots 7+20
1
2,6
3
4,5
0
0.25
0.50
0.75
1.00
Horizontal Load (Kg)


Root Tensions
25 Root system, 2 broken
Root tension (g)
1000
800
600
400
200
0
roots 6,21
1
2,25
5,22
3,24
4,23
0
0.25
0.50
0.75
1.00
Horizontal Load (Kg)


25 Roots per stem
Intact system
400 Seed-rate
C = compression
T = tension
T 1
T 2
T 3
T 4
T 5
T 6
T 7
C 8
C 9
C 10
C 11
C 12
C 13
C 14
C 15
C 16
C 17
C 18
C 19
T 20
T 21
T 22
T 23
T 24
T 25

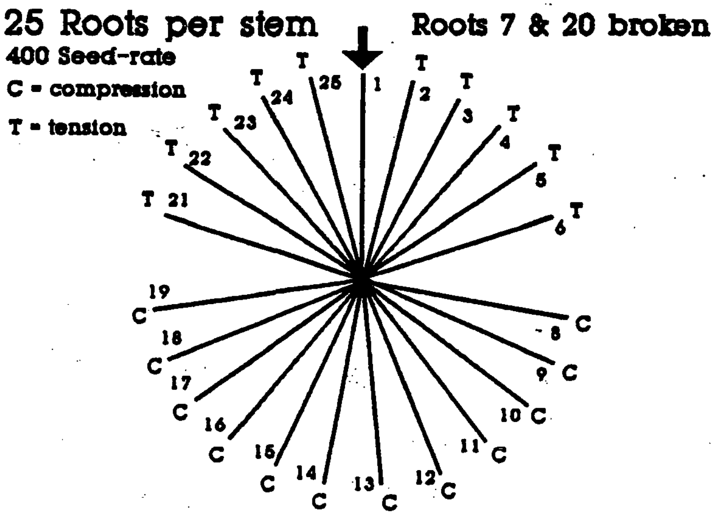

25 Roots per stem
Roots 7 & 20 broken
400 Seed-rate
C = compression
T = tension
1
T 2
T 3
T 4
T 5
T 6
C 8
C 9
C 10
C 11
C 12
C 13
C 14
C 15
C 16
C 17
C 18
C 19
T 21
T 22
T 23
T 24
T 25

Figure 8.1

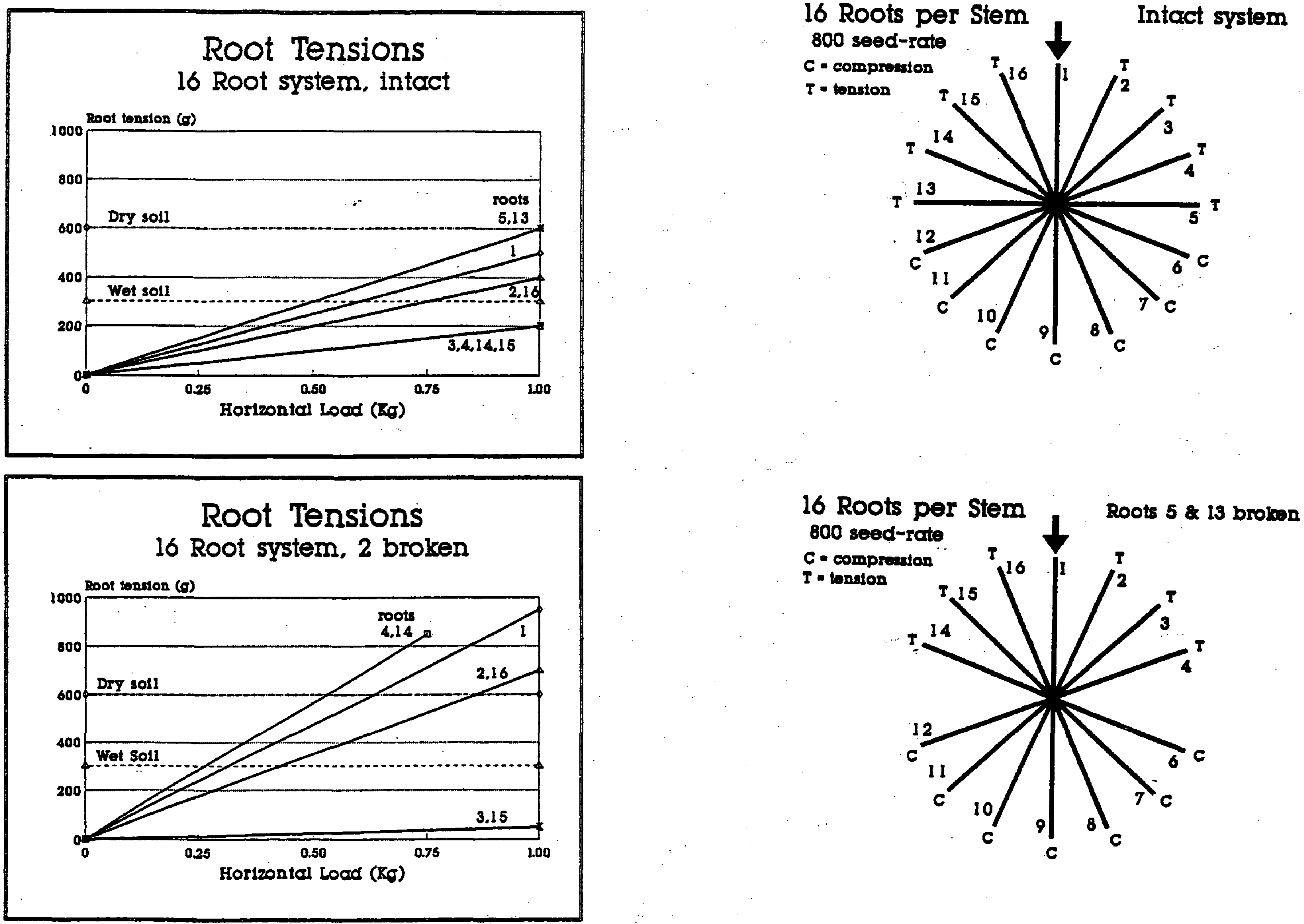
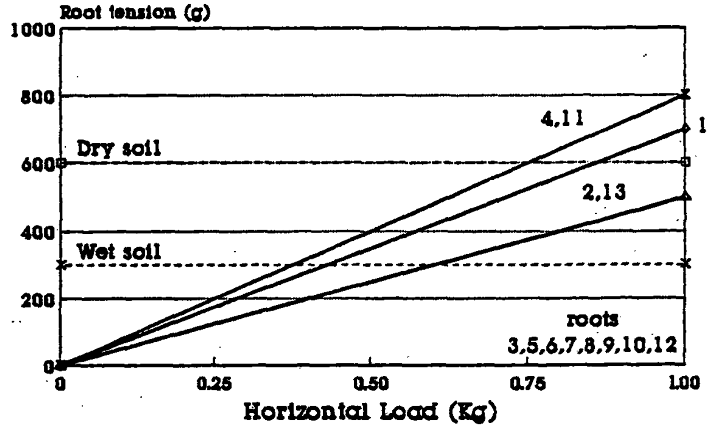

Root Tensions
16 Root system, intact
Root tension (g)
1000
800
600
400
200
0
Dry soil
Wet soil
roots
5,13
1
2,16
3,4,14,15
0
0.25
0.50
0.75
1.00
Horizontal Load (Kg)
Root Tensions
16 Root system, 2 broken
Root tension (g)
1000
800
600
400
200
0
Dry soil
Wet Soil
roots
4,14
1
2,16
3,15
0
0.25
0.50
0.75
1.00
Horizontal Load (Kg)
16 Roots per Stem
Intact system
800 seed-rate
C = compression
T = tension
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
T T T T T C C C C C C C T T T T
16 Roots per Stem
Roots 5 & 13 broken
800 seed-rate
C = compression
T = tension
1 2 3 4 6 7 8 9 10 11 12 14 15 16
T T T C C C C C C C T T T

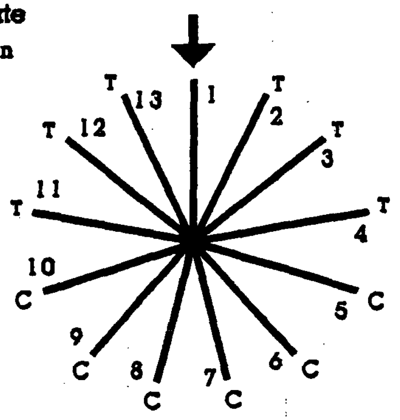
Figure 8.2

Root Tensions
13 Root system, intact

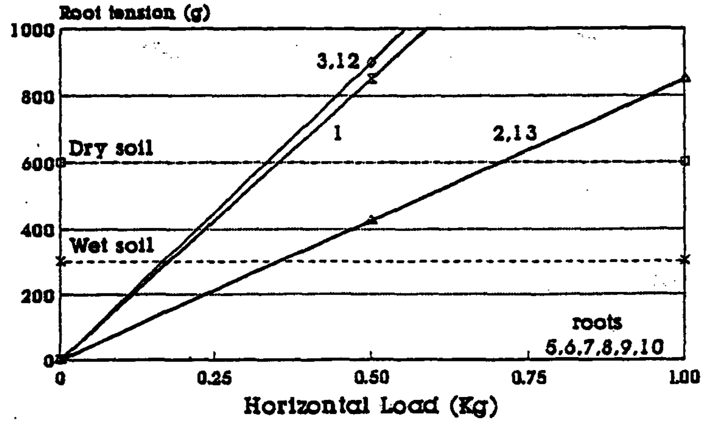


13 Roots per Stem
Intact system

1600 seed-rate
C = compression
T = tension



Root Tensions
13 Root system, 2 broken



13 Roots per Stem
Roots 4 & 11 broken

1600 seed-rate
C = compression
T = tension

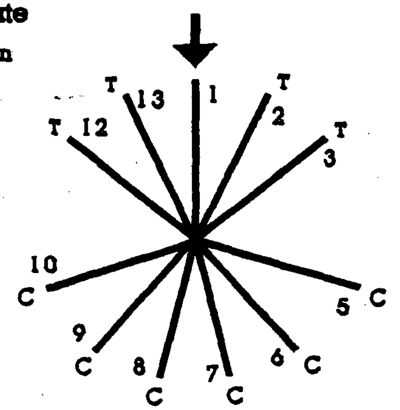
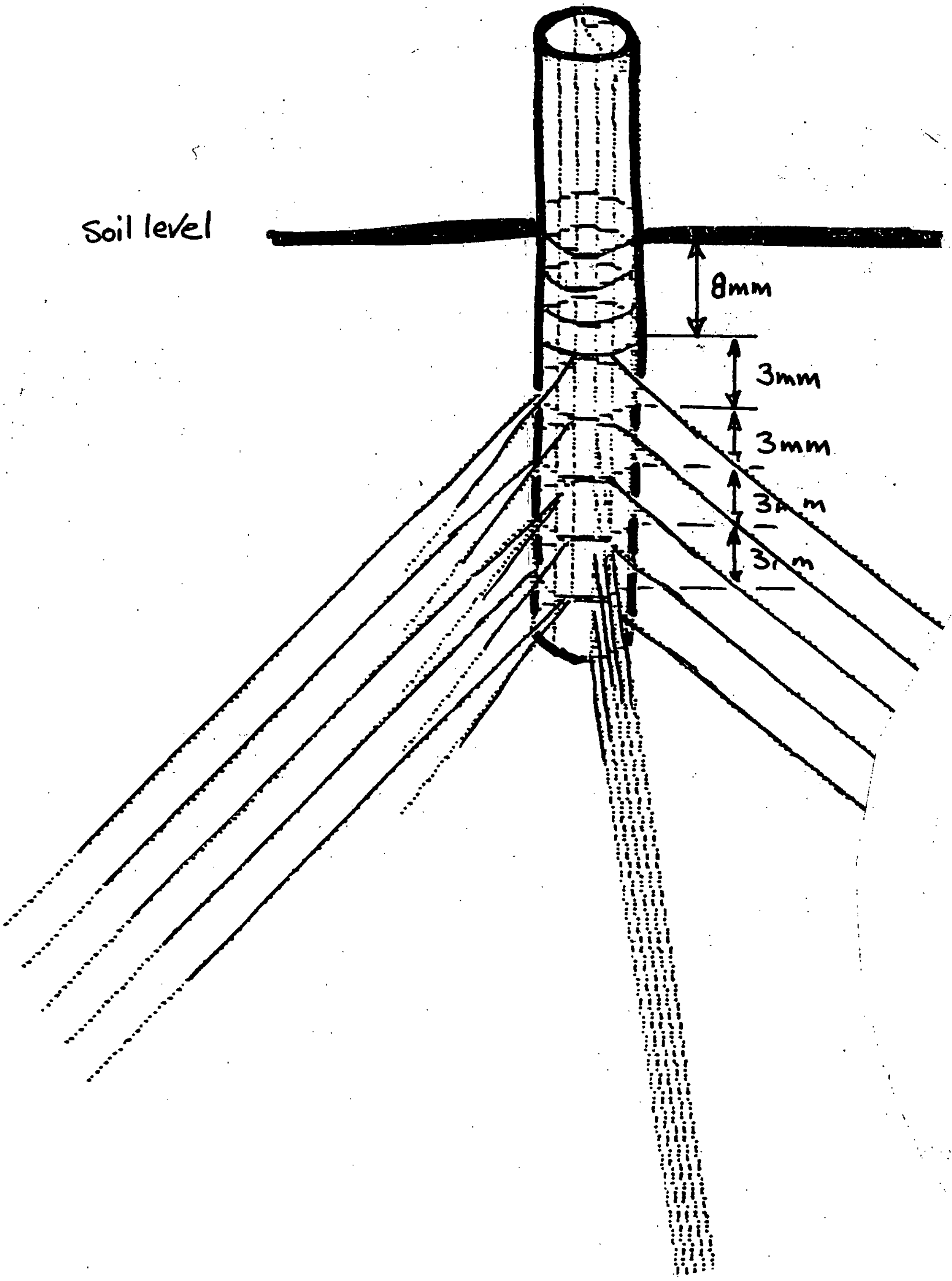


Figure 8.3

Figure 8.4

Structural model with roots attached
to crown internodes at various
depths.



overloaded but six others would still hold until there were further root failures. Lodging of the 400 seed-rate plots could therefore be more gradual than at the higher seed-rates.

This model does not take into account a number of significant factors. The loading from wind will not result in a steady load in one direction but will vary in magnitude and direction. Different roots will be placed under tension as the stem oscillates in response to the wind. Nevertheless, the overall principle of the model will hold good as the roots are evenly distributed round the stem. The model may be criticised in that it only considers a single horizontal force acting at the soil surface at the point of the crown from which all the roots also originate. In reality the majority of roots originate below the soil at depths of from 1mm to 5mm and across the width of the stem base which may be up to 4mm wide. Consequently there may also be a turning moment acting at the stem base and placing the roots in tension or compression. When the soil is wet, however, it provides little or no reaction so that there will be little or no leverage to create a moment. Leverage will therefore only occur as a result of the distance between the attachment points of the roots, and these distances are small. Such moments as would arise would still only tend to create tension within individual roots. A modification of the existing model structure is to have the roots attached at different positions to a solid base, representing the crown of the plant. The horizontal force would be applied at a given distance above the uppermost root.

A combined crown internode and variable depth root model

A second model root system was tested in which four roots were attached at each of five nodes spaced at intervals of 3mm down the stem below the ground. The first node was 8mm below the soil surface. The force was applied to the stem horizontally at the soil surface (Figure 8.9).

For this model it was assumed that before the soil becomes wet the stem section above the roots would be supported firmly by the soil so that the reaction to the horizontal force would come almost entirely from the soil and would be present in the stem as a horizontal shear force. As the soil becomes more moist and loses its strength the movement of the stem pushes the soil aside so that it no longer provides support at or near the soil surface and the shear force is carried by the stem lower in the soil. As this process continues and less and less support is provided by the soil in contact with the stem the support begins to come from the roots. Unrestricted movement of the stem places the roots in tension.

This range of conditions representing an increasingly wet soil providing less support was covered by running the analysis programme nine times. The conditions for each run are described below and the results presented in Table 8.1.

Conditions for root model runs:

1. Support to soil surface.
2. No support for 2.67mm depth.
3. No support for 5.33mm depth.
4. No support for 8.00mm depth.
5. No support for 11.00mm depth, including 1st root node.
6. No support for 14.00mm depth, including 1st and 2nd root nodes.
7. No support for 17.00mm depth, including 1st to 3rd root nodes.
8. No support for 20.00mm depth, including 1st to 4th root nodes.
9. No support for 23.00mm depth, including 1st to 5th root nodes.

Initially when the stem is supported principally by the strength of the soil near the soil surface the shear force acting on this region of the stem is relatively low. As the movement of the stem widens the hole the supporting region becomes lower on the stem and the shear forces increase due to the greater distance between the point through which the force is acting and the point of support. The maximum shear force acting on the stem was 958 kg Newtons, approximately 9.58 kg.

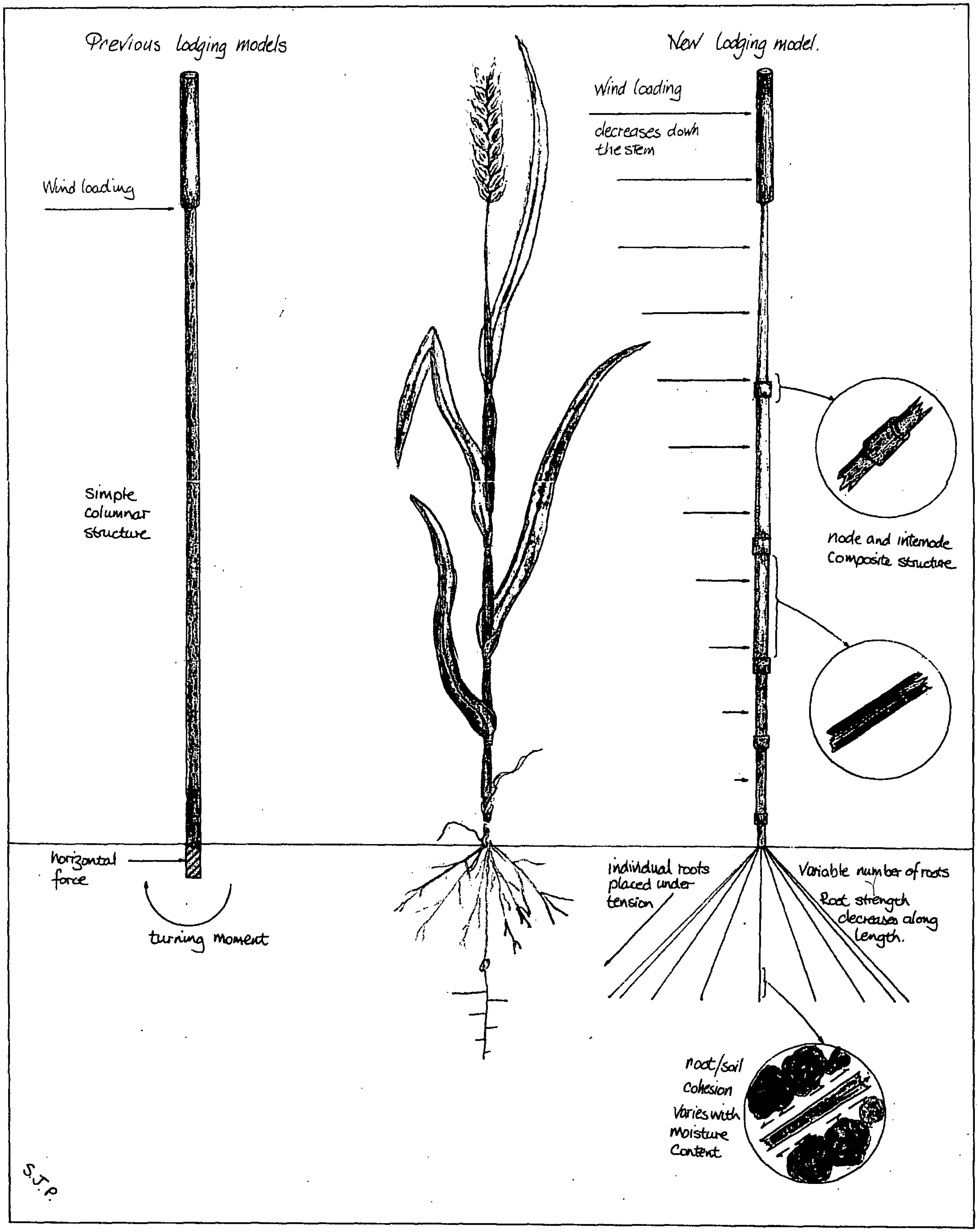

Previous lodging models
Wind loading
simple columnar structure
horizontal force
turning moment
New lodging model.
Wind loading
decreases down the stem
node and internode composite structure
individual roots placed under tension
Variable number of roots
Root strength decreases along length.
root/soil cohesion
Varies with moisture content
S.J.P.

Table 8.1

Forces acting in 3 dimensional root model as a result of a 1 kg horizontal load at the soil surface

Conditions	1	2	3	4	5	6	7	8	9
Maximum shear force in stem (kgN)	471	606	711	760	881	958	775	219	186
Maximum tension in roots at each node (kgN)									
1st node	0	0	0	0	2.7	9.6	20.6	97.5	125.4
2nd node	0	0	0	0	0	2.2	7.2	53.7	49.7
3rd node	0	0	0	0	0	0	3.3	44.8	14.5
4th node	0	0	0	0	0	0	0	16.9	29.8
5th node	0	0	0	0	0	0	0	0	92.2

When the stem is being supported by the soil above the roots very little tension is placed on the roots. However, once the 'hole' extends to below the point of attachment of the roots at each node the tension in the roots rises rapidly (Models 5 to 9) while the shear forces on the stem decline. Bearing in mind that the load required to pull a root from wet soil is about 30 KgN (300g) the stem would only be in danger of lodging from a horizontal force of 1kg if the 'hole' was greater than 17mm deep. If the horizontal force were increased to 3kg lodging might occur if the 'hole' was greater than 11mm deep.

Chapter 9

Final discussion

During the course of this project the complexities of all that is included in the term 'lodging' have been very apparent. The task of modelling the physical properties of the whole of the plant/soil system is much more complex than could have been achieved within our time-scale or resources. Nevertheless, progress has been made which it is hoped in the light of time will be shown to have advanced our understanding of lodging and how its damaging effects can be minimised.

That lodging is a serious problem for cereal growers throughout the UK needs little further support than that given by the data presented by Thomas (1982). In managing their crops the decisions of farmers regarding such inputs as nitrogen, variety, seed-rate and growth regulator are all influenced by the knowledge that if the summer is wet lodging could seriously reduce yields and grain quality.

The nature of the normal plant support system was observed closely in the first season of the project and was seen to fail gradually over a period of hours rather then suddenly in a cataclysmic failure. While the possibility of buckling of stems could not be entirely ruled out the evidence of both the initial stem bending tests with the Instron and of the field observations pointed to a more complex failure involving the crown of the plant, the roots and the soil.

As the project progressed the main thrust moved towards identifying the ways in which the plant support system could fail at the plant/soil interface when the soil properties change on wetting. As this would necessarily involve breakage or stretching of the roots the physical properties of the roots themselves were tested along the first part of their length. Although the breaking stress of the roots showed little change along their length the load they could bear before breaking declined as the diameter of the root decreased along its length. When pulled from soil roots tended to either break or core at 4cm to 6cm from the crown of the plant at loads within the range found during the root tensile tests. The pulling load for dry soil was in the range of 500g to 800g, similar to that of the strongest part of the root, while for wet soil the pulling load fell to 300g to 400g, similar to the strength of the roots 6cm to 8cm away from the crown.

The presence of from 13 to 28 roots capable of a combined load of from 4 to 22 kg to support each stem with a fresh weight of only 10g would suggest that there is little likelihood of failure of the root system. However when the forces actually occurring within the system were modelled using the methods of Finite Element Analysis it is clear that only a small number of roots are likely to be supporting the stem at any one time. If the cohesion between the soil and the roots were to fall to a low level then the roots being placed under the greatest tension would be likely to fail. In the models studied it was shown that a force equivalent to 1kg acting on the stem horizontally at the soil surface would be sufficient to lead to root breakage and lodging under wet soil conditions.

Although we were not able to proceed as far as modelling the stem system to derive the forces likely to be occurring at the stem base and transferred to the root system, data were collected and methods established which could be used for this purpose. In studying the structure of the aerial parts of wheat it was found to be particularly well designed for dissipating energy imparted to it by wind movement. During the oscillating action the composite material of the stem acts as a shock absorber, repeatedly absorbing and releasing energy until it is dissipated through the friction of one plant with another or in other ways. The damping action within plant stands was shown to have a very significant effect in reducing stem movement. Tests also revealed that wheat stems could undergo 'visco-elastic creep' if subjected to sufficiently severe vibration. However, further tests would need to be carried out to establish if this could occur at the sort of frequency and amplitude of oscillations which occur in the field.

The technique of using image capture from video footage showed considerable promise for establishing the relationship between weather events, stem movement and lodging. However, we were not able to pursue the technique in this project after initial attempts were hampered by the particularly dry and lodging free 1989 season. Nevertheless, the relationship between weather events on a micro-scale and lodging would also need further study in order to derive how wind movement relates to stem movement.

A summary of the findings from the various parts of this project can be found in Table 9.1

Towards an integrated theory of the lodging process

In parallel with the detailed study of the various components of the plant support system an attempt was made to unravel these strands to develop a more complete theory of lodging, taking account of its inherent complexity. Lodging has largely remained an unsolved mystery because both the weather and the crop are subject to random and unpredictable variations which complicate the known and predictable progression of crop ontogeny. Furthermore, complexity exists because of the wealth of conclusions from experiments showing relationships between many characteristics and lodging. Scientists have also persisted in trying to find one mechanism which explains the phenomenon rather than taking account of all that is happening in each situation. It is our contention that a theory of lodging which incorporates the whole system rather than homing in on one part of it will be both more truthful and more useful.

A Theory of Lodging

Under dynamic loading by the wind the stem will deflect. The stem may or may not have an additional static loading due to rain water retention on its surface. The deflection depends on the flexural rigidity of the stem, i.e. EI, its material and geometric properties, and is reduced due to damping by neighbouring stems. The static loading of the stem, i.e. its fresh weight, and its material properties will change throughout the grain filling period. The loading and deflection are unlikely to be large enough to result in local buckling of the stem leading to lodging.

The deflection and loading generate a bending moment and shear force at the base of the stem where it is fixed, i.e. unable to deflect. This force and bending moment are resisted by the root/soil system. Root tensile strength, root number, root/soil cohesion and soil shear strength determine the resisting force. The root tensile strength in turn depends upon the cross sectional area of the root and the root/soil cohesion and shear strength upon the soil type and moisture content.

Lodging occurs when a critical loading is generated by the aerial shoot system which the root/soil system is unable to resist leading to its failure. Greater critical loadings can be supported without failure by the root/soil system when there are:

* higher numbers of roots per stem
* thicker roots
* drier soils

Critical loading therefore depends on both the crop and the weather. Allowing for variation in the root system due to ontogeny, critical loading will vary because of changes in soil wetness relating to rainfall and its interception by the crop canopy.

The loading generated by the aerial shoot system will be increased by greater deflection, which in turn is increased by:

* thinner stems, i.e. lower I's
* longer stems
* lower elastic moduli (E)
* fewer stems, i.e. less damping
* higher fresh stem weights
* higher fresh ear weights
* stronger winds
* greater rain water retention on the plant surface, which depends on rainfall, wind and the surface area of the plant

In response to any given set of weather conditions, the loading generated by crops will vary because of variation in the crop characteristics which are involved in determining the loading. This loading response coefficient will change as the crop develops and individual characteristics alter with ontogeny. Management and weather conditions govern the growth and development of the crop and therefore also govern the crop characteristics involved in determining both the critical loading and the loading response coefficient.

For each crop loading response coefficient and critical loading can be determined based on knowledge of how weather and management influence the crop and how the critical loading and loading response coefficient depend on crop characteristics. From these the risk of lodging can be determined for a defined set of weather conditions. However, to be of value, mathematicising of this theory to produce a model will also have to include the facility to predict lodging risk at earlier stages in crop development when it is still possible to make and implement management decisions which can reduce the risk of lodging. Incorporation of existing models such as ARCWHEAT to predict later crop growth and development should be possible.

Formulation of a model of lodging based on this theory will involve the following steps:

(1) determining the critical loading and loading response parameters
(2) determining the relationships between the critical loading and loading response parameters and crop characteristics
(3) determining the effects of management and weather factors on these crop characteristics.

Much of the theory and knowledge necessary is already available to formulate the model. Tuning and sensitivity testing would have to be carried out to make it as accurate and concise as possible without unnecessary complexity.

Practical implications

While this project may appear to have been largely a theoretical study it could be of significance in a number of ways. The general perception of lodging among the farming community is that it is a stem related problem. This emphasis may have been encouraged by the association of shorter strawed varieties and of straw shortening growth regulators with increased lodging resistance. The results of this project should therefore help to increase the awareness that the failure during lodging is more likely to be in the root/soil system. In a scenario in which chemical inputs to crops are being increasingly questioned the possibility of finding methods of improving lodging resistance through soil cultivation treatments needs to be considered along with possible ways of stimulating or strengthening the roots themselves. Consolidation of the soil by rolling has always had mixed results with cereals through the risk of soil capping or over compaction. However, it may be that carefully carried out soil compaction treatments could enhance lodging resistance. Plant breeders may also be encouraged to look for lodging resistance through characteristics other than straw length and stiffness. These characteristics do not always correlate well with lodging resistance but it may be that in some cases by selecting for lodging resistance improved root systems have already been selected for.

The development of the 'lodging model' which was originally envisaged in this project and which would enable high lodging risk situations to be identified has been brought nearer but not yet achieved. If accomplished such a model could firstly, enable more rapid progress to be made without the need for as many expensive, time-consuming and often inconclusive field experiments and, secondly, provide a practical means of identifying high lodging risk situations in sufficient time for some remedial action to be taken.

Table 9.1

Summary of main findings from experimental programme

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a) The findings from the experiments on the aerial shoot system were:

- Local buckling of the stem happened at very large deflections (73cm in plants with 5 internodes).
- Breaking loads (i.e. stress x cross-sectional area) of 300g -500g were measured.

Breaking loads of internodes:

- increased down the stem and were not linearly related to their diameters.
- were greater at lower N rates.
- were similar in the two varieties, Norman and Longbow.
- did not vary with maturation of the internodes but in mature internodes the displacement at buckling was smaller.

During grain filling:

- Length and diameter of stem internodes changed little.
- Fresh and dry weights of internodes increased and then decreased.
- The ear continued to increase in fresh and dry weight after the stem internodes had begun to lose weight.

- Growth regulator reduced the length of stems.
- Nitrogen had small effects on length and fresh and dry weight of stems.
- Visco-elastic creep can occur in stems under unnatural conditions of vibration and temperature.
- Damped deflections of the ears of a crop in a windrun of 10 k/h of up to +/- 14cm were observed.

b) The findings from the experiments on the root/soil system were:

- Breaking load of roots is linearly related to their diameter which decreases with distance from the crown.
- Root diameter and therefore breaking load decreased at higher seed-rates but was unaffected by growth regulator.
- Breaking stress and elastic modulus were greater at higher N rates but root diameter was unaffected by N.
- Soil root cohesion was greater in dry soils than in wet soils as indicated by greater breaking loads, 500-600g in dry soil, 300-400g in wet soil. Roots were displaced by 6-8mm. However, length of the broken roots was similar at all soil wetness.
- Lodging occurred earlier at higher seed-rates.
- Individual stems may retain about 2g water on their surfaces, i.e. equivalent to about 20% of their fresh weight at 500stems/m^2.

At seed-rates of 50, 200 and 400 seeds/m^2:

- stem numbers/m^2 were similar.
- root numbers /stem showed a two-fold variation, increasing with seed-rate.
- root weights/stem varied with seed-rate but not linearly, being lowest at 200 and highest at 400 seeds/m^2.

At higher lodged seed-rates compared with lower unlodged seed-rates:

- stem numbers/m^2 were almost double at the higher seed-rate.
- fresh weight/m^2 was lower at the higher seed-rate, therefore fresh weight/stem was reduced by half at the higher seed-rate.
- root numbers were reduced by 2-3 per stem at the higher seed-rate.
- length of the longest root was reduced by 16% at the higher seed-rate.
- dry weight of roots per stem was reduced by 2/3 at the higher seed-rate.

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Appendix 1

Description of Lodging events in 1988 Crop

19th July 1988

Isolated patches of lodging had appeared in the field area. These were of no regular size or shape, and there was no discernible pattern to their distribution. The prevailing weather conditions were of persistent light rain and moderate but gusty wind.

1. There was no directional orientation of the lodging. The stems seemed to have fallen at random, not downwind of the prevailing wind.

2. Stems did not seem to be broken.

3. No obvious reason for the failure of the stems could be discerned.

20th July 1988

The isolated patches of lodging had increased in size, but not in number. The whole crop had begun to lean, generally downwind. The wind had lessened, and the rain turned to a fine drizzle.

1. The lodging had increased in a downwind direction and was most pronounced where plants had collapsed into an already lodged area.

2. Previously lodged plants had degenerated rapidly and some now showed signs of stem damage, especially where they lay across other plants.

3. Lodged plants had accumulated a lot of surface water.

4. The whole crop was leaning, and its movement in response to the wind appeared sluggish.

5. Leaning in the field experimental plots seemed to occur away from plot edges, the leaning being most pronounced in the middle of the crop.

6. Some plants seemed to be contacting or leaning on others, especially at plot edges where some plants were upright.

21st July 1988 (Morning)

Isolated areas of lodging had increased in size in the same way as before. The rest of the crop however, was now leaning dramatically. Some of the high nitrogen plots were almost flat. The weather was again moderately windy with light but steady rain.

1. There was a marked difference between the leaning of the high nitrogen and low nitrogen plots.

2. The plants with the greatest angle of lean did not respond to any but the strongest gusts of wind.

3. The plants with the most dramatic angles of lean were not orientated directly downwind, but rather in fan formations, apparently radiating from an origin, with random orientations sixty degrees either side of the wind direction.

4. The leaning and flat plants did not have the usual springy elastic properties associated with wheat plants.

5. Leaning plants seemed to gather surface water.

21st July 1988 (Afternoon)

The plants were watched throughout the day, with periodic rain continuing although the wind lessened considerably.

1. Leaning in all plants continued to get worse as the day progressed.

2. This seemed to occur by the gentle "relaxation" of the plants into a horizontal position.

3. The plants lying flat were examined and found not to have any obvious stem damage except for the marked loss of elasticity.

4. No evidence of broken roots was found on examination of the plants although examination was made difficult by the very wet soil and the large number of fallen plants.

Conclusions

i) Lodging was not a sudden event but tended to take place over a period of hours during which time the crop, constantly moving due to the action of the wind, initially returned to the vertical from each movement and then began to lie at an angle before gradually becoming fully lodged.

ii) The lodging which first occurred on the 14th July took place on a day when there was no rainfall, although over 11mm had fallen over the previous 2 days (Figure 3). The windrun, however, was high on the 14th and the lodging was observed as occurring during a period of high wind. Further lodging occurred on 17th July, again a relatively dry day following two days with higher rainfall (5.4mm and 3.8mm respectively) but on which the wind-run again reached a peak. Further lodging took place during the period from 18th to 21st July during which there fell a total of 10mm of rain, but with a drop in windrun.

iii) Similar weather periods occurred again after the period during which the main lodging took place, but during which no significant increases in lodging were observed. Over the 24th and 25th July a total of almost 10mm rain fell and the windrun was almost double the earlier figure.

iv) Lodged areas were examined closely for evidence of the form of damage which occurred. The area of lodging studied occurred along 8m of a 10m by 2m wide plot. Lodging extended across the full width of the plot, but the adjacent plots, which had received lower rates of nitrogen, did not lodge. The direction of lodging was predominantly across the plot, but some areas lodged down the plot or at an in-between angle. The pattern of lodging would be consistent with the effects of gusting wind. The soil was noted as being 'moist' but not 'wet' and appeared structurally sound. Five $1m^2$ quatrats were examined in detail. Five to ten percent of the stems showed physical damage. In three of the five quadrats there was clear evidence also of plants pulling away from the soil.

1990

Extensive lodging took place in the seed-rate/variety experiment and detailed recording of the lodging and weather events was made. In Figures 3.3 and 3.4 the lodging events, meaned over the 4 varieties, are plotted against the hourly data for rainfall, windspeed and wind direction. Graphs of the incidence of lodging in each variety at the six seed-rates are given in Figure 3.5.

Lodging was first observed on the morning of Monday 4th June in the 1600 seed-rate plots of all four varieties. On Friday 1st June 11.6mm of rain had fallen and on the 2nd 1.7mm. Lodging, accounting for over 57% of the plot areas could have occurred on the 2nd, 3rd or early on the 4th June. A further 33% increase in lodging at the 1600 seed-rate was observed on 6th June after rainfalls of 2.5mm and 5.9mm on the 5th and 6th. The windrun which was high on the morning of 4th was lower on the 5th and very low for most of the 6th. Rainfalls of 8.4mm and 1.2mm occurred on the 7th and 8th July along with high winds. Lodging in the 800 seed-rate plots which had reached 25% on the 6th increased by a further 28% and at the 400 seed-rate reached 10%.

From the 9th to 17th June there was no rainfall and the windrun figures were low. Nevertheless, a further increase in lodging, to virtually 100% of the 1600 seed-rate plot areas, was recorded on 11th

June. At the same time the 800 and 400 seed-rate plots appeared to recover from some of the lodging recorded in them on the 7th and 8th. The rainfall of 9.7mm and 9.2mm on the 17th and 18th June resulted in increased lodging observed on the 18th. Once again lodging scores taken a few days later on 20th June indicated a partial recovery from lodging at the 800 and 400 seed-rates. In the 1600 seed-rate plots some geotropic bending upwards at the upper nodes of the stems was observed on 18th June, but these stems were easily lodged again by further rain.

In spite of moderate rainfalls of up to 8mm over the 21st to 25th June no further increase in lodging was seen. However, 11mm of rain on the 26th can be associated with a 10% increase in the 800 seed-rate plots. Substantial rainfalls occurred over the weekend of 30th June to 1st July along with strong winds on the 1st, but no further lodging was observed when a score was taken on the 2nd July. In fact the 1600 and 800 seed-rate plots showed some recovery by bending at the nodes. However, this recovery was lost on July 5th and 9th as a result of 14.5mm of rain over the 3rd and 4th and 13.1mm over the 6th and 7th followed by high winds in both cases. On the 9th July 24% of the 400 seed-rate and 7% of the 200 seed-rate plot areas lodged.

Each of the further increses in lodging which occurred mainly in the 800, 400 and 200 seed-rate plots can be associated with the rainfall periods which occurred on the 15th and 16th July, 27th and 29th July, 9th, 10th and 13th August. On the 15th and 16th July, however, windspeeds were relatively low.

Appendix 2

Field Experimentation, Materials, methods and results

1988

Management factors, namely nitrogen and growth regultor, were included in the field experiment to investigate their influence on lodging and plant characters associated with lodging susceptibility. The variety Slejpner was sown on 14th October 1987 at a seed-rate of 180 kg/ha (450 seeds per m^2) into a seed-bed prepared using conventional cultivations and to which a fertilizer dressing of 80kg/ha P_2O_5 and K_2O had been applied. A total of 72 plots 2m by 15m were arranged in three blocks. The experimental treatments were as shown in Table 10.1. Details of the treatments and other aspects of the management of the crop are given in Table 10.2. Plant, stem and ear counts and straw height measurements were carried out on 6 half meter row lengths at the appropriate times of the season. The plots were harvested using a 'Claas' plot combine and visual assessments of the plot area lodged were recorded at the time of harvest. The grain yield, straw height and lodging data are presented in Table 10.3.

Table 10.1

Experimental treatments, 1988 experiment

Nitrogen levels	150 kg/ha	250 kg/ha		
Chlormequat	None	early	late	split
Ethephon	None	Terpal	Cerone	

Table 10.2

Management details, 1988 experiment

Twin-tak CF		19th April
Early chlormequat	2.5l/ha	19th April
Late chlormequat	2.5l/ha	19th April
Split chlormequat	1.75l/ha	19th April
	0.75l/ha	10th May
Terpal + wetting agent	1.5l/ha	14th May
Cerone + wetting agent	1.0l/ha	14th May
1st N dressing	50kg/ha	24th February
2nd N dressing	100kg/ha	13th April
High N plots	150kg/ha	26th April
Sportak Alpha	1.5l/ha	27th May
Radar	0.5l/ha	24th June
Stem Count		25th May
Harvest date		12th September

Table 10.3

Results of 1988 Field Experiment

	Grain yield kg/ha	Straw height cm	Lodging % of plot
	Low N, 150 kg/ha		
Untreated	7743	79.4	0
Chlormequat			
early	6138	64.1	0
late	6916	65.9	0
split	7128	67.0	0
Ethephon			
alone	6307	62.3	0
+ mepiquat chloride	7189	65.0	0
+ chlormequat	7220	72.5	0
	High N, 300 kg/ha		
Untreated	4711	77.5	53.3
Chlormequat			
early	8639	70.4	16.7
late	7374	73.1	30.0
split	8203	71.1	17.8
Ethephon			
alone	7278	74.7	17.8
+ mepiquat chloride	7371	69.9	16.7
+ chlormequat	8909	67.5	3.3

1989

An experiment was conducted to investigate the relative importance of soil wetting and of displacement of the wheat plant stems as contributory factors to lodging using nitrogen and growth regulators to create a range of lodging risks.

A split-plot randomised block design was used in which the main plot treatments were:-
i) Added water, applied to the plots from a slurry tanker. The plots were laid out on sloping ground and it was intended that the water would run down the length of the plot. The water was applied on 30th June, but the ground was so dry and cracked that even the large quantities of water being applied disappeared rapidly into the soil and did not wet the majority of the plot area.

ii) Repeated crop displacement. This treatment was applied by passing a 4" dia plastic pipe, held horizontally at a height of about 45cm, down the plot 4 times in succession. This treatment was applied immediately after the water application both to plots which had recieved and those which had not received water.

The sub-plot treatments were low N (150kg/ha) and high N (250kg/ha) each with no growth regulator, chlormequat (Cycocel) or ethephon with mepiquat chloride (Terpal) treatments.

The variety Slejpner was sown on 31st October 1988 at a seed-rate of 191 kg/ha (450 seeds per m^2) into a seed-bed prepared using conventional cultivations and to which a fertilizer dressing of 80kg/ha P_2O_5 and 120kg/ha K_2O had been applied. Details of the treatments and other aspects of the management of the crop are given in Table 10.4. Plant, stem and ear counts and straw height measurements were carried out on 6 half meter row lengths at the appropriate times of the season. The plots were harvested on 9th September 1989 using a 'Claas' plot combine and visual assessments of the plot area lodged were recorded at the time of harvest.

Neither the water nor the lodging treatments had any visible effect on the crop on 30th June and in view of the excessively dry conditions further attempts to apply water to the plots were abandoned.

Grain yields were consistently high, and were significantly greater with 150 kgN/ha than with 250 kgN/ha. A small amount of lodging occurred at the higher N level as the crop ripened but the lower yield is more likely to have been due to higher levels of incidence of yellow rust which signifcantly reduced the thousand grain weight (Table 10.5).

Table 10.4

Management details, 1989 Field Experiment

Previous Crop		Flax	
Twin-tak CF		18th April	
Chlormequat	2.5 l/ha	3rd May	1st node
Terpal + wetter	2.0 l/ha	10th May	2nd node
1st N dressing	70 kg/ha	30th March	
Low N plots	80 kg/ha	26th April	
High N plots	180kg/ha	26th April	
Sportak Alpha	1.5 l/ha	17th May	
Tilt 250EC	1.0 l/ha	5th June	
Mistral +	0.75 l/ha		
Radar	0.5 l/ha	15th June	
Stem Count		26th May	
Ear Count		22nd June	
Crop height		28th June	
Harvest date		9th September	

1990

The principal management factors related to lodging were included in two experiments with a view to creating a range of 'lodging risks' from very high to low. In one experiment nitrogen and growth regulator were the main treatments and in the other, variety and seed-rate. Details are given of the variety/seed-rate experiment in Table 10.6 and the results summarised in Table 10.8. Details of the nitrogen/growth regulator experiment are given in Table 10.7 and the results in Table 10.9.

Characteristics measured in the variety/seed-rate experiment were:
i) Root numbers and properties.
ii) Above ground plant characteristics.
iii) The timing and nature of lodging events.
iv) The hourly weather (rainfall, windspeed and direction) associated with lodging events.
v) The difference between lodged and unlodged areas immediately after lodging events in terms of both above ground and below ground characteristics.
vi) Components of yield and combine yields.

In addition to these experiments 3 sets of wheat plots were sown in an eight point 'star' arrangement with the objective of determining if there was an association between the direction of sowing and the risk of lodging.

Table 10.5

1989 Field Experiment,
Yields and components of yield

	Growth Regulator				N level kg/ha		
	Unt	CCC	Ter	sig	150	250	sig
Grain yield (kg/ha)	9545	9848	9508	NS	9814	9453	*
Straw yield (kg/ha)	4304	4205	4264	NS	3871	4644	***
Total DM yld (t/ha)	12.42	12.63	12.29	NS	12.21	12.68	NS
Plants/m^2	318	333	314	NS	232	321	NS
Stems/m^2	512	517	508	NS	513	511	NS
Ears/m^2	524	540	521	NS	511	546	***
TGWT (g)	39.74	39.37	38.67	***	40.61	37.91	***
Grains per ear	45.8	46.2	47.2	NS	46.36	46.41	NS
Hectolitre wt (kg)	76.03	75.69	76.11	*	75.84	76.04	NS
Straw height (cm)	72.3	68.4	68.3	***	68.9	70.5	***
Lodging % of plot	8.5	2.3	7.1	NS	0.3	11.7	***

The variety/seed-rate experiment

Extensive lodging occurred in the variety/seed-rate experiment providing data on the timing and nature of lodging events, the nature of the crop at the time of lodging and the effects of seed-rate and variety on lodging. The incidence of lodging in this experiment and the relationship between weather events and the lodging are discussed in Chapter 3.

Both seed-rate and variety significantly affected a number of the yield components. The interactions were not significant so the effects of seed-rate were relatively consistent across the four varieties. The main factor contributing to lodging was seed-rate and although it is not possible to separate fully the effects of seed-rate and of lodging on yield, by considering the timing of the lodging in relation to the growth of the crop, some assessment can be made of the direct effect of the lodging.

The number of ears and the number of grains per ear would have been largely determined before any lodging occurred and if other factors had been equal the yield difference over the seed-rates attributable to them them would have been less than 10% (Figure 10.1). The number of ears per plant which developed fell from nearly 7 at the lowest seed-rate to 1.3 at the highest while the number of grains per ear fell from 56 to 15. Thousand grain weight declined by over 20% over the range of seed-rates and the smaller grain size is also reflected in the higher proportion of smaller sized grains in the sieved samples (Figures 10.2 and 10.3).

Table 10.6

Management details, 1990 Variety/seed-rate Experiment

Previous crop		Oilseed Rape
Sowing date		29th September 1989
Astrol	3.5 l/ha	16th November
Talstar	75 ml/ha	16th November
N dressing	178 kg/ha	28th March
Radar	0.5 l/ha	23rd April
Sprint	1.5 l/ha	18th May
Mistral	1.0 l/ha	13th June
Stem count		16th May
Ear count		8th June
Crop height		23rd July
Harvest date		7th September

Table 10.7

Management details, 1990 Nitrogen/PGR Experiment

Previous crop		Wheat	
Sowing date		2nd October 1989	
Astrol	3.5 l/ha	16th November	
Talstar	75 ml/ha	16th November	
1st N dressing	50%	29th March	
2nd N dressing	50%	30th April	
Chlormequat	2.5 l/ha	6th April	Pseudo-stem erect
Terpal + wetter	2.0 l/ha	2nd May	2nd node
Radar	0.5 l/ha	23rd April	
Sprint	1.5 l/ha	18th May	
Mistral	1.0 l/ha	13th June	
Stem count		4th May	
Ear count		11th June	
Crop height		20th July	
Harvest date		3rd September	

Table 10.8a
Winter Wheat Seed-rate Variety Experiment 1990
a) Effects of seed-rate

SEEDRATE	50	100	200	400	800	1600	s.e.m.
Grain yield	9512	9647	7807	5631	4184	2758	379.8
Straw yield	4290	4434	4112	3849	3213	3292	242.0
Plants/m2	41.7	80.6	151.2	260.2	391.5	640.4	10.58
Stems/m2	317.3	374.8	449.3	505.3	568.5	858.0	20.63
Ears/m2	253.3	326.0	388.7	480.7	635.0	854.7	16.69
TGWT	53.50	53.97	52.83	47.78	44.73	42.67	.917
Grains/ear	55.90	53.08	47.93	33.34	23.10	15.28	1.569
Hectoltr wt	71.50	71.38	71.28	69.50	68.57	68.33	0.416
>2.8mm	87.6	86.3	87.9	78.3	54.9	54.7	3.65
>2.5mm	12.56	9.29	8.30	13.20	23.08	19.39	2.150
>2.2mm	2.49	3.11	2.67	5.81	14.36	16.38	1.525
<2.2mm	1.88	1.35	1.16	2.79	7.74	9.66	1.038
Height(cm)	84.54	86.50	88.87	89.27	86.95	84.82	0.662
Fert hds	85.8	95.2	107.2	116.4	113.8	116.2	7.56
Infert heads	0.25	0.17	0.67	2.17	10.25	32.75	2.163
Total DM yld	12375	12634	10748	8635	6769	5659	498.4
Fshwt ers(g)	18.16	17.22	15.12	13.56	10.79	8.82	0.355
Fshwt m2	4.61	5.56	5.75	6.39	6.79	7.49	0.245

10.8b Effects of Variety

VARIETY	APOLLO	HORNET	LONGBOW	NORMAN	s.e.m.
Grain yield	7386	7480	5744	5767	310.1
Straw yield	4938	4071	3235	2925	197.6
Plants/m2	248.3	261.3	261.8	272.2	8.64
Stems/m2	547.0	484.0	500.0	517.9	16.84
Ears/m2	540.7	456.9	464.0	497.3	13.63
TGWT	47.03	51.08	48.39	50.49	0.961
Grains/ear	35.44	43.77	37.24	35.96	1.281
Hectoltr wt	72.63	70.51	68.93	68.29	0.340
>2.8mm	80.9	77.7	71.1	70.0	2.98
>2.5mm	14.25	11.99	15.14	15.84	1.755
>2.2mm	4.89	6.62	9.22	9.14	1.245
<2.2mm	2.98	3.76	4.59	5.06	0.847
Height (cm)	85.85	84.11	93.00	84.34	0.541
Fert heads	122.3	104.0	101.3	95.3	6.18
Infert heads	4.17	3.17	7.78	15.72	1.766
Total DM yld	11217	10428	8408	7827	407.0
Fshwt ears(g)	11.43	15.83	14.24	14.27	0.29
Fshwt m2	5.637	6.508	6.012	6.236	0.20

The yields in the 200, 400, 800 and 1600 seed-rate plots progressively declined from the 9.6 t/ha harvested from the 100 seed-rate plot to only 2.8 t/ha at the 1600 seed-rate. It is likely that the relatively early onset of lodging in the 1600 seed-rate plots, and subsequently at the lower seed-rates, while the crops were still green and grain filling was taking place, was a major factor in the yield reductions. In the absence of lodging it would be expected that the highest yields would be obtained from the plots with about 400 ears/ m^2, i.e. the 200 or 400 seed-rates (Darwinkel, 1978).

However, the harvested yield fell to only 2.8 t/ha at the 1600 seed-rate. This was only 50% of the yield calculated from the sampled components and this wide discrepancy would suggest that there were also large losses during combine harvesting of the lodged plots.

The nitrogen/PGR experiment

This experiment suffered from a 'take-all' infection which resulted in very poor grain yields and an absense of lodging even at the highest level of N applied. Only a small number of samples were taken from this experiment.

Effect of sowing direction on lodging

The effect of different directions of sowing relative to the direction of the prevailing wind was investigated by sowing eight wheat plots 2m by 20m in a star arrangement. Three replicate 'stars' were sown within a field area of wheat. When lodging occurred in the field area the pattern of lodging in the star plots was observed from a height of 15m using a hydraulic gantry. Combine yields were also taken from each plot. There were no significant differences between the plots in yield or in lodging which could be attributed to direction of sowing.

Table 10.9
Winter wheat N & PGR experiment, 1990
Yield and components of yield

a) Effects of N level

	N Level kg/ha						
	NIL	60	120	180	240	300	sig
Grain yield (kg/ha)	1493	2739	3199	3921	3987	4114	***
Stems m-2	498	558	628	708	668	753	***
Ears m-2	302	379	373	403	405	461	***
TGWT (g)	32.4	30.3	29.0	29.0	30.1	29.5	NS
Grains per ear	25.6	31.9	38.8	44.7	44.4	47.3	***
Hectolitre wt (kg)	70.8	69.2	68.7	68.6	68.6	68.3	NS
Straw height (cm)	43.8	54.5	61.2	64.2	65.3	63.9	***
Lodging % of plot	0	0	0	0	0	0	NS

b) Effects of PGR treatment

	none	CCC	Terpal	sig
Grain yield (kg/ha)	3407	3289	3030	NS
Stems m-2	646	632	629	NS
Ears m-2	387	395	379	NS
TGWT (g)	30.4	30.1	29.6	NS
Grains per ear	37.1	39.4	39.8	NS
Hectolitre wt (kg)	69.3	68.7	69.1	NS
Straw height (cm)	62.4	58.7	55.4	***
Lodging % of plot	0	0	0	NS

Figure 10.1

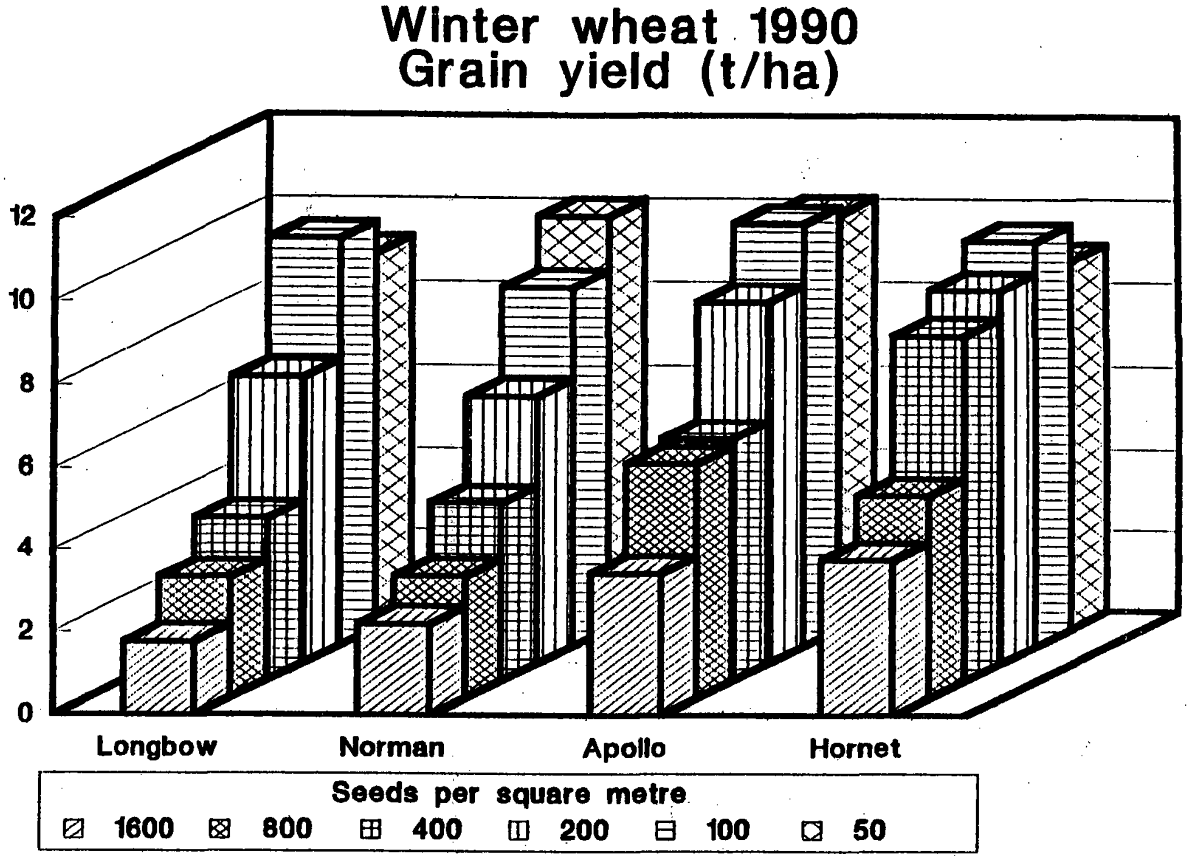
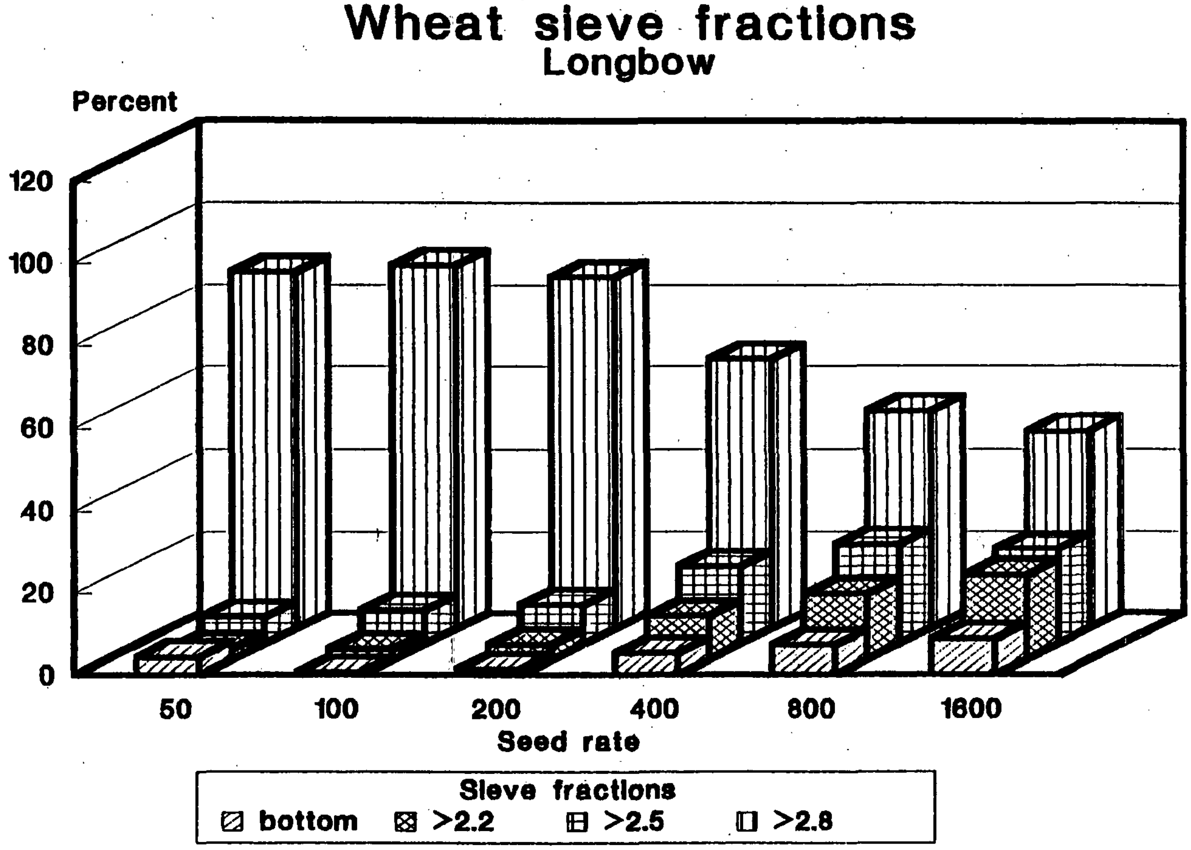


Figure 10.2



Appendix 3

Methods for recording wind and stem movement

i) A portable weather station was set up with anemometers at three heights (30cm, crop height and 200cm) and set to record once per second.

ii) In stands of wheat adjacent to the weather station strongly growing plots were selected for study.

iii) The end of the plot was trimmed to ground level to leave a clean 'face' of crop.

iv) Individual plants were selected and marked at each node with a high contrast fluorescent tag.

v) A scaling frame 50cm by 50cm was fixed close to the face of the crop and levelled.

vi) A portable 8mm video camera was set up on a tripod and adjusted so that the scaling frame filled the screen. A red filter was used on the camera to maximise the contrast to show the movement of the markers at each node.

vii) The time facility on the camera was synchronised with the weather station so that videoed stem movement could be correlated with the causal windrun.

viii) During a period in which there were sufficiently strong winds to cause stem movements the selected stands were videoed.

ix) The marked plants were then harvested and material property and stem geometry measurements taken.

x) The video recording was transferred to VHS standard. It was intended that 'frame grabbing' techniques would be used to analyse the stem movements.

Appendix 4

Definitions of technical terms

2nd moment of inertia:	I The resistance of a body to angular acceleration.
Damping ratio:	The ratio of the natural frequency of a independent oscillating body to the frequency of the same body surrounded by n similar bodies subject to the same driving force.
Euler buckling:	Buckling along the length of a long thin column.
Flexural rigidty:	A measure of how difficult it is to deform a structure. It is dependent upon the nature of the material and the geometry of its structure.
Hooke's Law:	In an elastic material strain is proportional to stress.
Modulus of Elasticity:	E (Young's Modulus) Ratio of the stretching force per unit of x-sectional area to the elongation per unit length (stress/strain).
Moment:	The turning effect of a force measured by the product of the force and the perpendicular distance of the point from the line of action of the force.
Newton:	Force which accelerates a mass of 1 kg by 1 metre per second.
Strain:	The proportion of the original dimensions by which the structure deforms.
Stress:	The load applied per unit cross-sectional area to a structure.
Visco-elastic creep:	A composite material may undergo slippage between its elastic and viscous components. This has the effect of making the whole become more viscous. This phenomenon usually occurs in response to increased temperatures and prolonged or repeated loading.