PROJECT REPORT No. 305

TO ESTABLISH SEPARATE STANDING POWER RATINGS FOR STEM AND ROOT LODGING IN THE UK RECOMMENDED LISTS FOR WHEAT

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by

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This is the final report of a 40-month project which started in September 1999 with a grant of £175,832 from HGCA (Project No. 2213).

CONTENTS

ABSTRACT

Previous HGCA-funded research has shown that crops should be managed differently to reduce stem and root lodging: establishing fewer plants and rolling before GS30 are the best methods for reducing root lodging; delaying and reducing fertilizer N are best for reducing stem lodging. So far, winter wheat varieties have not been assessed for their risks to stem and root lodging separately and the current standing powers are a combination of both types. Therefore, the two primary objectives of this project were to investigate:

1) whether winter wheat varieties differ in their rankings for stem and root lodging risk.

2) methods for rapidly assessing stem and root lodging risk.

1) This project, carried out at 3 sites during 3 seasons, concluded that about half of the 15 varieties studied had significantly different rankings for stem and root lodging risk. In individual varieties, standing powers for stem and root lodging could differ by as much as 3. Significant alterations in crop management are required to change lodging risk by the equivalent of one standing power. These include: reducing plant establishment by about 50 plants m^{-2} to increase root lodging standing power; delaying and reducing fertilizer N for a GAI of 5 to increase stem lodging standing power; applying chlormequat or delaying drilling by 2 weeks to increase both types of standing power. Thus it seems clear that separating standing powers for stem and root lodging would enable better targeting of crop management to strengthen specific variety weaknesses and that this would significantly improve lodging control.

2) Two approaches (A & B) were developed for measuring separate standing powers for stem and root lodging.

Approach A involves measuring selected characteristics of the anchorage system, stem base and shoot, then using a model of lodging to calculate the lodging risks. This approach is very reliable and requires data from 4 trials per year to classify the varieties into 5 significantly different standing powers. Sufficient data to develop a dual standing power guide would be achieved after the 3rd year of trials. As a result of this project, the time required to take the measurements and process the data has been reduced by about 30% through the development of better laboratory apparatus and the identification of the most critical plant characters. This means that this approach will take 75 person days per year.

Approach B involves using a lodging instrument to quickly measure lodging resistance in the field. This approach requires 1-2 person days to measure one trial and was shown to correctly predict lodging at the 2 test sites in 2002. Resistance to stem lodging was successfully measured at all sites, but soil close to field capacity and crops with strong stems are required to measure the resistance to root lodging successfully. Therefore, this approach will require pilot testing on a range of soil types in the Recommended List trials to prove its ability to identify root lodging standing powers without irrigation or special crop management.

SUMMARY

INTRODUCTION

The potential yield of a field of winter wheat is reduced by 5% for every 10% of the field area that lodges early (Stapper & Fischer 1990). Additionally, lodging often reduces Hagberg falling number to below that required for bread making. It is clear therefore that every effort must be made to minimize lodging to help achieve profitability**. Since lodging can occur through either stem or root failure there is scope to improve lodging control by managing crops to avoid BOTH stem and root lodging.** HGCA-funded research has shown that reducing plant establishment and rolling before GS30 are the best methods for reducing root lodging, whereas delaying and reducing fertilizer N are best for reducing stem lodging (Berry *et al.* 2000). So far winter wheat varieties have not been assessed for their risks to stem and root lodging separately and the current standing powers are a combination of both types. Therefore the two primary objectives of this project were to 1) investigate whether winter wheat varieties differ in their rankings for stem and root lodging risk, and 2) identify methods for rapidly assessing stem and root lodging risk.

1) Do winter wheat varieties have different standing powers for stem and root lodging?

METHODS

Experiments. Fifteen winter wheat varieties were grown in six randomized block experiments between 2000 and 2002. Three experiments were done at ADAS Rosemaund in Herefordshire (silt clay loam), two at ADAS Boxworth in Cambridgeshire (clay) and one at Sutton Bonington in Leicestershire (sandy loam). The varieties had a wide range of standing powers (shown in brackets) and included Buster (9), Cadenza (6), Charger (5), Consort (8), Equinox (9), Harrier (6), Hereward (8), Hussar (6), Madrigal (8), Mercia (6), Reaper (5), Rialto (6), Savannah (7), Shamrock (8) and Spark (7). All varieties were sown at 375 seeds m^{-2} and sowing dates ranged from 3-22 October. Irrigation was applied to the Rosemaund and Sutton Bonington sites to induce lodging after the plant characters associated with lodging had been measured. Up to 25 mm water was applied per day on between 4 and 8 days between GS75 and GS85.

Measurements. Measurements of the plant characters associated with lodging were made during grain filling (GS71 to GS79). Ten plants were selected randomly from one half of each plot, avoiding the outer three rows, and the natural frequency was measured on each main shoot before the plants were excavated with a hand fork to a depth of about 100mm. The intention at sampling was to ensure that the structural crown roots were completely recovered. Laboratory measurements included the spread and depth of the root plate; the number of shoots per plant; the height at centre of gravity and ear area of each main shoot; together with the length, diameter, wall width and breaking strength of each of the bottom two internodes. The

methods for these measurements are described in detail by Berry *et al.* (2000). A visual assessment of the percentage area of crop that was lodged was made within the unsampled half of each plot. During lodging assessments, the dominant mechanism and point of failure was identified, i.e. whether by stem failure or anchorage failure. Assessments were done after each rain event or irrigation treatment, or weekly during dry periods between ear emergence and harvest.

Calculation of failure wind speed. The measurements of the lodging associated plant characters were used to calculate the leverage of the shoot and plant, the strength of stem and anchorage system, and the wind speed to cause stem and root lodging (stem and root failure wind speeds). Equations for these calculations are described on pages 16-17. **The most important calculations are for the stem and root failure wind speeds because these are used to quantify the relative stem and root lodging risks of a variety.** The failure wind speeds of each variety can be used to estimate the chance of lodging by using the probability distribution for experiencing extreme wind gusts during the summer shown in Fig. 1. The solid line shows that there is a probability of greater than 0.9 of experiencing a wind speed of at least 10 ms^{-1}, which drops to less than 0.1 for a wind speed of at least 17 ms^{-1}. This relationship can be used to estimate the chance of experiencing the stem failure wind speeds. For root lodging to occur it is assumed that at least 7mm rain must fall to weaken the soil in addition to experiencing the root failure wind speed. The dashed line in Fig. 1 represents the chance of experiencing different wind gusts during the same day that >7mm of rain falls. This relationship can be used to estimate the chance of experiencing the root failure wind speeds.

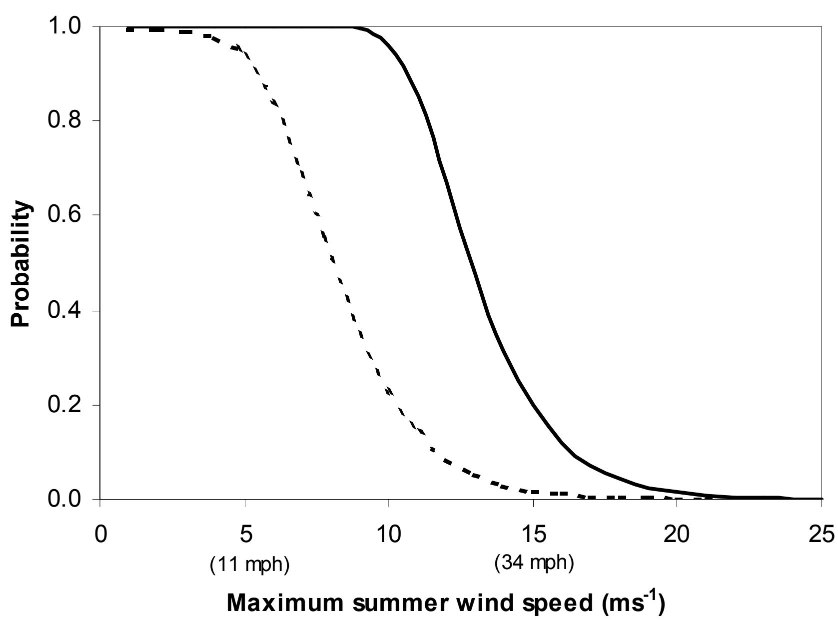

Fig. 1. Probabilities of experiencing wind gusts independent of rainfall (—) and wind gusts with ≥7 mm daily rain (---) between mid June and mid August within the main wheat growing regions of the UK. From Berry *et al.* (2003).

RESULTS

In spring, the average plant population of each experiment ranged from 200 to 282 plants m^{-2} due to variation in establishment for the different sites and seasons.

Both root and stem lodging were observed in the field experiments. Root lodging was the predominant form at Boxworth in both years, Rosemaund in 2001 and at Sutton Bonington in 2002, with stem lodging more common at Rosemaund in 2000 and 2002. Across all site/seasons, root lodging varied from 2% for Hereward to 47% for Cadenza. Stem lodging varied from 0% for Consort to 19% for Cadenza. This degree of late season lodging, caused by natural weather events or through irrigation, was enough lodging to test the model's calculations of root and stem lodging risks (calculated in terms of failure wind speed). **This showed that both stem and root failure wind speeds correlate well with the observations of lodging (R^2 = 0.65 and 0.60), which gives further confidence that the model's output is a reliable indicator of lodging risk.**

An analysis of variance (ANOVA) was carried out to investigate how site/season and variety affected the stem and root failure wind speeds. The variety differences in failure wind speed were highly significant ($P<0.001$), although the rankings of some varieties did change between sites and seasons ($P<0.05$) Further analysis showed that these ranking changes were relatively small and occurred in only 4 varieties. As a result of this we have presented the mean stem and root failure wind speeds of the varieties across all of the sites and seasons (Fig. 2). The ANOVA also showed that the variety rankings for stem failure wind speed were significantly different from the rankings for root failure wind speed ($P<0.001$). Importantly these differences in rankings were consistent across the sites and seasons. **This statistical analysis, done for all six site/seasons, demonstrates that the variety rankings for stem lodging are significantly different to the rankings for root lodging.**

The ANOVA also showed significant differences between sites and seasons ($P<0.001$). On average, the root and stem failure wind speeds varied from 7 ms^{-1} to 14 ms^{-1} for the different sites and seasons. This was surprising considering that all crops received similar management and suggests that soil type and weather conditions during the growing season have a large influence on the lodging susceptibility of crops. The sites and seasons affected the stem and root failure wind speeds by different amounts ($P<0.001$). For example, the average stem failure wind speed was 3.4 ms^{-1} greater than the average root failure wind speed at Rosemaund in 2000 and 2.4 ms^{-1} less at Sutton Bonington in 2002. These observations illustrate how the balance of stem and root lodging risk can be altered in different environments.

Fig. 2 shows that the root and stem failure wind speeds were not well correlated and a linear regression between the two only accounted for 33% of the variation. On average, the stem failure wind speed was 1.2 ms^{-1} greater than the root failure wind speed. Varieties which deviate significantly from this average difference will have different rankings for stem and root lodging resistance. Therefore varieties lying significantly above the best fit line will be ranked higher for root lodging resistance than for stem lodging resistance and varieties lying below this line will have a greater ranking for stem lodging resistance. **Fig. 2 shows that varieties with a greater resistance to root lodging (compared with stem lodging) include Savannah (P<0.05), Rialto, Buster and Hereward (P<0.10). Varieties with a greater resistance to stem lodging include Cadenza, Spark (P<0.05) and Mercia (P<0.10).**

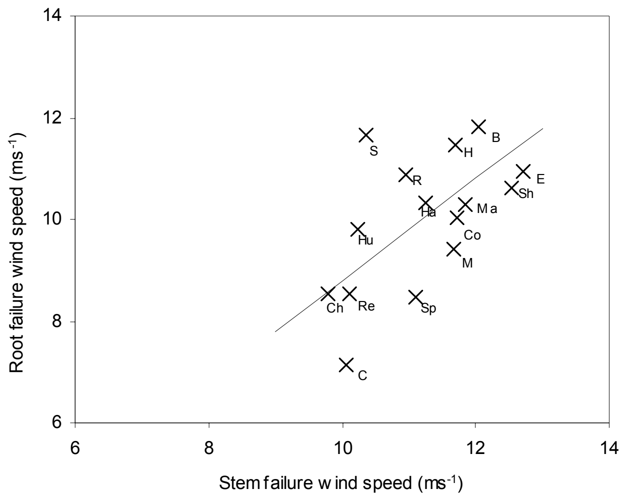

Fig. 2. Stem failure wind speed plotted against root failure wind speed for 15 winter wheat varieties, averaged over all sites and seasons; B-Buster, C-Cadenza, Ch-Charger, Co-Consort, E-Equinox, Ha-Harrier, H-Hereward, Hu-Hussar, Ma-Madrigal, M-Mercia, Re-Reaper, R-Rialto, S-Savannah, Sh-Shamrock, Sp-Spark. The mean difference between the stem and root failure wind speeds is represented by y= x –1.2 (—). The SED for the interaction between type of failure and variety = 0.594 ms^{-1} (162 df).

Significant differences were observed between the varieties for all of the lodging associated plant characters over all sites and seasons (P<0.05). This confirmed that these characters are variety traits. An analysis of the variety differences for each plant character together with their impact on lodging risk (quantified in Berry *et al*., 2003) would indicate which traits breeders should select for to realise the greatest increase in lodging resistance. Several pairs of traits were linked, but **importantly no correlations were detected between the plant characters that determine the strength of the stem base and the anchorage system. This helps explain why the variety susceptibilities towards stem and root lodging were not well correlated.**

The calculation of separate standing powers for stem and root lodging.

This section outlines a method for classifying the root and stem lodging resistances of varieties into a dual standing power scheme. The implications of these standing powers for lodging control are then considered. Absolute values for the stem and root failure wind speeds of different varieties cannot be considered directly because they change between sites and seasons. However, this study has shown that the differences in failure wind speed between varieties are consistent between sites and seasons, so it is possible to use these, and the differences from the failure wind speed of Charger are shown in Table 1. Charger was chosen because it has a similar ranking for both stem and root lodging. In order to classify the varieties we have assumed that Charger has a standing power of 5 for both stem and root lodging and the most resistant variety for either stem or root lodging has a standing power of 9. This means that each standing power classification spans 0.8 ms^{-1} for both stem and root lodging. Finally, we assume that Charger is in the middle of its standing power classification which means that a standing power of 5 ranges from –0.4 ms^{-1} to +0.4 ms^{-1}. **Table 1 shows that 10 of the 15 varieties have different standing powers for stem and root lodging. Five of these varieties have differences of at least two standing powers.**

Table 1. *A method for classifying separate standing powers for stem and root lodging*

Variety	Stem lodging: Failure wind speed deviation from Charger (ms^{-1})	Stem lodging: Classification for stem lodging (1-9)[a]	Stem lodging: Probability (P) of lodging when P=0.1 for the most resistant variety	Root lodging: Failure wind speed deviation from Charger (ms^{-1})	Root lodging: Classification for root lodging (1-9)[a]	Root lodging: Probability (P) of lodging when P=0.1 for the most resistant variety
Buster	2.26	8	0.14	3.28	9	0.10
Cadenza	0.28	5	0.35	-1.38	3	0.68
Charger	0.00	5	0.39	0.00	5	0.44
Consort	1.92	7	0.16	1.51	7	0.23
Equinox	2.92	9	0.10	2.42	8	0.15
Harrier	1.46	7	0.20	1.78	7	0.21
Hereward	1.90	7	0.16	2.92	9	0.12
Hussar	0.45	6	0.32	1.26	7	0.26
Madrigal	2.06	8	0.15	1.77	7	0.21
Mercia	1.87	7	0.17	0.90	6	0.31
Reaper	0.33	5	0.34	0.02	5	0.44
Rialto	1.17	6	0.23	2.36	8	0.16
Savannah	0.56	6	0.31	3.12	9	0.11
Shamrock	2.74	8	0.11	2.09	8	0.18
Spark	1.31	7	0.22	-0.02	5	0.45
SED (18 reps 151 df)	0.285			0.724		
LSD (5%)	0.563			1.430		

[a] A standing power of 3 ranges from -2.0 to -1.2 ms^{-1}, 4 (-1.2 to -0.4 ms^{-1}), 5 (-0.4 to 0.4 ms^{-1}), 6 (0.4 to 1.2 ms^{-1}), 7 (1.2 to 2.0 ms^{-1}), 8 (2.0 to 2.8 ms^{-1}), 9 (>2.8 ms^{-1}).

Separating the standing powers by a failure wind speed of 0.8 ms^{-1} means that the standing powers would be significantly different for stem lodging because the Least Significant Difference (LSD) for the stem failure wind speeds is 0.56 ms^{-1} (Table 1). However, this would not be the case for root lodging because the LSD for the root failure wind speed is 1.43 ms^{-1}. For root lodging standing powers to be significantly different ($P<0.05$), the number of plots used in this study must be trebled. This could be achieved after three years by growing 4 trials per year, each with 35 varieties replicated twice. In the current Recommended Lists, the LSD for standing power is 1.5 times the size of one standing power interval. If this criteria is used then only 360 plots would be required, but the standing power classifications would be less reliable.

How these classifications for stem and root lodging relate to probabilities of lodging depends upon how the crop has been managed and how the weather affected its growth. If we assume that the most resistant variety has a 10% chance of lodging then the lodging probabilities can be estimated for the other varieties using Fig.

1. This demonstrates that some varieties have large differences in their probabilities for stem and root lodging when the most resistant varieties within an experiment have identical risks to stem and root lodging. For example, the stem and root lodging probabilities for Savannah are estimated to be 0.31 and 0.11 respectively, demonstrating that this variety is three times as likely to stem lodge. Spark, Cadenza and Mercia are about twice as likely to root lodge.

The effects of management decisions on lodging risk have been quantified by Berry *et al.* (2000; 2002). These findings have recently been adjusted to account for better specified aerodynamic characteristics of the shoot (Sterling *et al.* 2003). We have expressed these management effects on lodging risk in terms of their effect on the standing powers for stem and root lodging (Table 2). This shows that root lodging resistance is improved by the equivalent of a single standing power by reducing plant establishment by about 50 plants m^{-2} (over the range of 400 to 200 plants m^{-2}). Our unpublished data indicates that this trend continues below 200 plants m^{-2}. Rolling the soil in the spring would be expected to increase the standing power for root lodging by one. Resistance to stem lodging is reduced by two standing powers by sowing on soil with about 30 kg ha^{-1} more residual N. This effect would be almost reversed by reducing and delaying fertilizer N to target a green area index of 5. Both types of lodging resistance are improved by between one and two standing powers with a split application of chlormequat. Delaying drilling by 2 weeks would raise both standing powers by one. Thus it is clear that a change by one standing power is equivalent to significant changes in crop management. Therefore, **the varieties with different standing powers for stem and root lodging will benefit from special management to prevent excessive susceptibility to either type of lodging.**

Table 2. *Effect of crop management on the standing powers for stem and root lodging.*

Factor	Change to husbandry	Change in standing power for STEM lodging	Change in standing power for ROOT lodging
Soil residual N in spring	Increase by 30 kg N ha^{-1}	-2	-1
Sowing date	Per week delay	+0.5	+0.5
Plants m^{-2}	Per 50 plants m^{-2} reduction	+0.5	+1
PGRs	Split chormequat	+1 to +2	+1 to +2
Fertiliser N	Reduce and delay (target GAI 5)	+1.5	+1.5
Spring rolling	Pre-GS30	0	+1

2. Methods for rapidly assessing stem and root lodging.

In the previous section of this Summary it was shown that that there are significant differences between varieties in their ability to resist root and stem lodging. However, the methods used to establish this were rather time consuming for adoption in routine variety trials. Also in current variety trials there is a significant problem in assessing lodging resistance as it can only be assessed when lodging occurs. Significant amounts of lodging occur only at a minority of trial sites. Thus two approaches were investigated to resolve these problems.

Approach A investigated how to shorten the time required to measure the plant characters which were used in the first section of this report to calculate the stem and root failure wind speeds.

Approach B investigated whether an instrument could be developed that could directly measure stem and root lodging resistance in the field.

APPROACH A.

The protocol required to calculate stem and root failure wind speeds is described in the Technical detail section (p15-16). The following bullets summarise how we shortened this protocol.

- Measuring the failure moment of the bottom internode rather than the bottom two internodes.
- Calculating stem failure moment from stem breaking strength and the internode length only and omitting measurements of stem diameter and wall width.
- Laboratory apparatus was developed to speed up the measurement of stem failure moment.
- Using ear dimensions to estimate ear area 0.87(ear length x maximum ear width) predicted 90% of the variation in the true ear area. This avoided the need for an image analyser.

The number of plants assessed could not be reduced below 10 per plot without adversely affecting precision.

We estimate that incorporation of the time saving methods would reduce the time to assess a plot by about 30%, so in one day one person could measure 5 plots or process the data from 15 plots.

APPROACH B.

Development of apparatus and procedures

Several methods for measuring stem and root lodging resistance in the field were considered which centred around a device for measuring the force required to displace cereal shoots. The pros and cons of automating the device were weighed, i.e. whether it should be tractor mounted or have a mechanically operated pushing arm. It was concluded that a manually operated device should be developed that would not require skilled operators and which could be reproduced cheaply. The main criteria were that it should 1) measure the lodging resistance of several dozen shoots simultaneously, 2) have an adjustable pushing bar height, 3) be portable within the field and 4) be easily dismantled for transport between sites. Measurement of the resistance to root lodging presented a further challenge, which we hoped could be overcome by testing during wet soil conditions when the soil was weak.

During the first year a field-based instrument for measuring the resistance of about 70 shoots against rotational displacement was designed and built (Fig.3). The instrument was operated by placing the pushing plate at an appropriate height against the wheat stems and raising the rotating handle in 5^{o} increments. This forced the pushing plate against the shoots and the force required to do this was recorded by the load cell. Initial field tests showed that the instrument could detect small differences between the pushing resistances of varieties. Tests in the 2nd year investigated the procedure that enabled the lodging instrument to identify the variety differences with the greatest accuracy and efficiency. This involved testing different numbers of rows, angles and direction of displacement, duration of each test and applying the force at different heights. These tests showed that isolated rows of cereals had to be tested at several angles between 40^{o} and 70^{o} to determine the force required for stem and anchorage failure. Pushing height was also shown to be critical, but direction of displacement and duration of test did not have an effect. Further calculations were later carried out in collaboration with engineers from Birmingham University to determine which pushing height should be used to account for differences in shoot leverage. A replicate lodging instrument was also built in this year and its practicality tested by the NIAB. From this suggestions were made for improving its portability and ease of use.

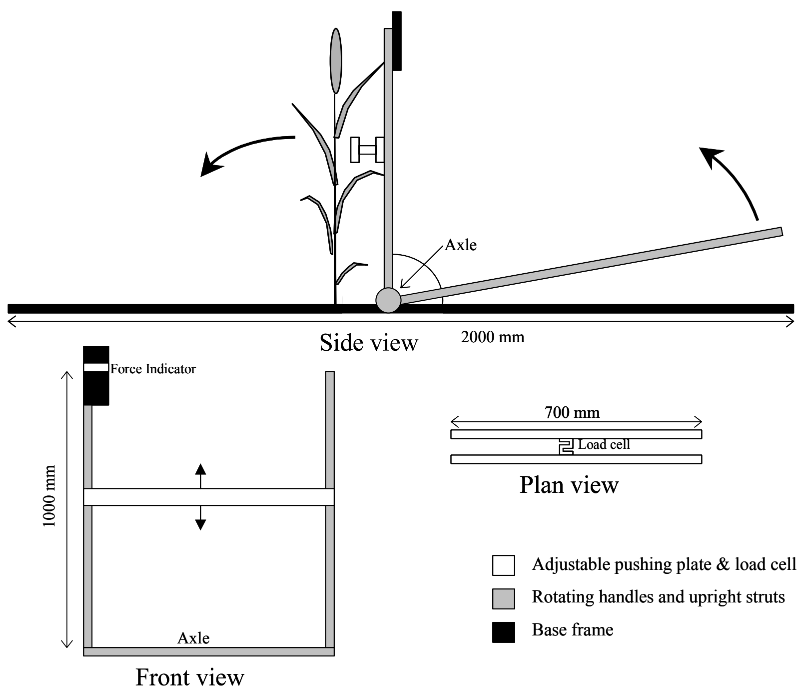

Fig. 3. Diagrams of the lodging instrument from the side, front and top.

In the 3rd year, two methods for rapidly assessing lodging resistance were tested. These methods were based on the developmental work carried out in the first two years. Method 1 accounted for the height induced differences to shoot leverage and estimated the force (in Newtons) required to push the shoots over. Method

2 was more sophisticated and accounted for the way that the wind interacts with the shoot to generate leverage. Method 2 estimated the stem and root failure wind speeds, but required additional measurements of the height at centre of gravity, natural frequency and ear area. Susceptibility to stem lodging was assessed when the soil was dry and strong, whereas susceptibility to root lodging was assessed after the soil had been weakened by irrigation. Tests were done on 14 winter wheat varieties grown at ADAS Rosemaund and Sutton Bonington during 2001-2. The NIAB tested the practicality of the instrument by performing Method 1 at three sites.

Results

The crops at Rosemaund experienced stem lodging, with variety differences in the percentage area lodged ranging from 1 to 74%, whereas crops at Sutton Bonington experienced root lodging (1 to 60%). Method 1 accounted for 59% and 50% of the stem and root lodging respectively (Figs 4a and b), whereas Method 2 accounted for 63% and 53% respectively (Figs 4c and d). These levels of predictive power compare very favourably with the amount of lodging variation which is accounted for by the current standing powers. The results show that Method 1 is the best procedure because it is the most rapid yet produces a similar level of performance as Method 2. **These results are encouraging and represent the first successful large-scale testing of an instrument for measuring the lodging resistance of wheat.** Pilot tests by the NIAB showed that 64 plots could be measured on dry soil in only 4 hours. We conclude that assessing lodging resistance using the lodging instrument is an advance over assessing amounts of natural lodging because **it will provide a non-subjective estimate of the lodging risk for every variety in every year.** It should be noted that between 1995 and 1999 only 10% of R.L. trials experienced lodging in >75% of their varieties, thus illustrating the problems with relying on natural lodging to formulate standing powers. A single set of measurements with the lodging instrument requires a similar amount of time per trial as the assessments of natural lodging which are currently carried out several times per year.

In these experiments the lodging instrument did not detect significantly different rankings for the resistance to stem and root lodging. This was because; 1) too few plots were evaluated to enable small effects to be detected by the statistical analysis, 2) High soil residual N at RM caused weak stems to develop, about 30% of which buckled during the root lodging tests and 3) Difficulty with wetting the soil to field capacity after it had dried and cracked also resulted in some stem buckling during the root lodging tests. The principal function of the lodging instrument for measuring lodging resistance has been proven, so it seems probable that it can detect differences in stem and root lodging risk if sufficient plots are tested and given more favourable conditions that enable the resistance to root lodging to be measured accurately. To confirm this further tests would need to be done on several soil types when they are at, or close to, field capacity and where the soil residual N is low or moderate to promote the development of strong stems. Alternatively soil types with weak soil and that are easily wetted could be identified specifically for root lodging tests. Carrying out the tests earlier (soon after anthesis), when the stems are stronger, would also reduce the likelihood of stem buckling during the root lodging tests.

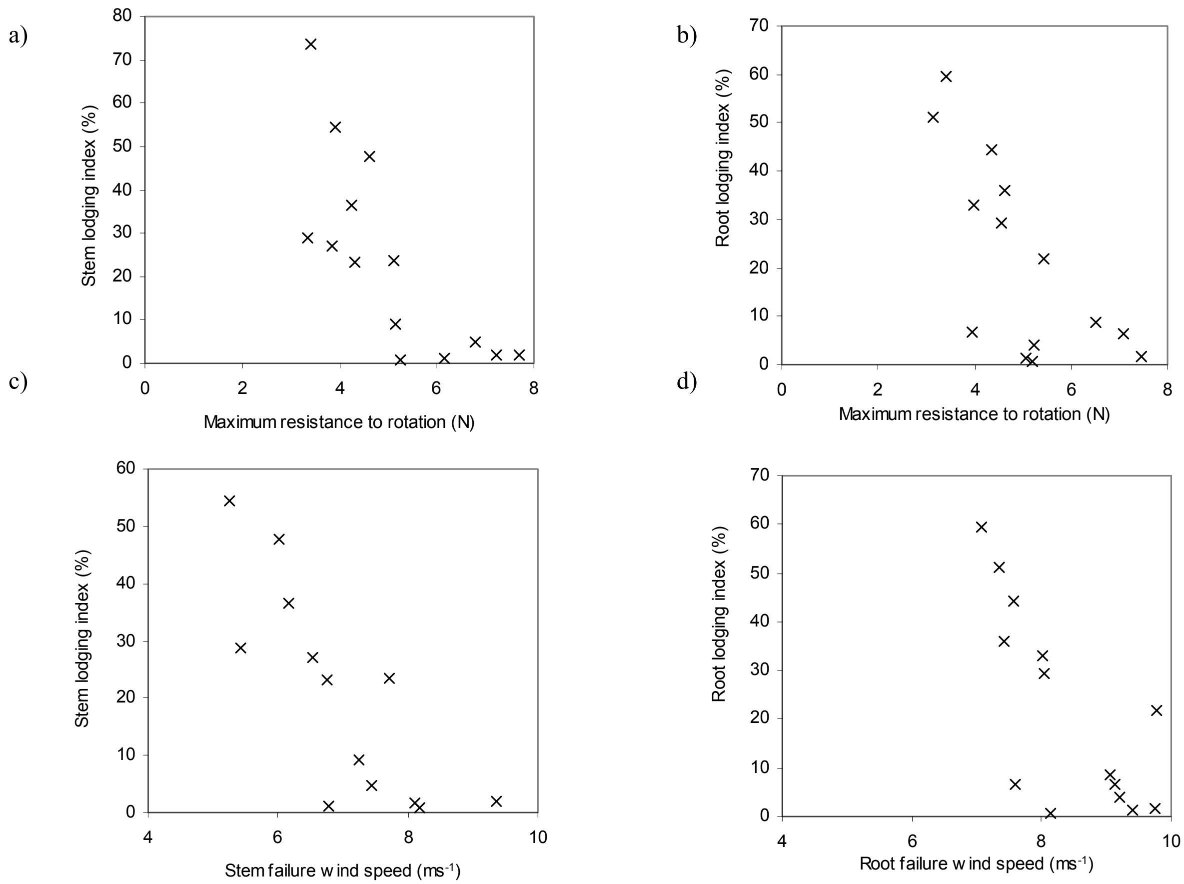

Fig. 4 a) Maximum rotational resistance for a row of shoots in dry soil plotted against stem lodging index at Rosemaund (RM) (y= -12.4x + 87; R^2=0.59).
b) Maximum rotational resistance for a row of shoots in wet soil plotted against root lodging index at Sutton Bonington (SB) (y= -11.1x + 77; R^2=0.50).
c) Failure wind speed for shoots in dry soil plotted against stem lodging index at RM (y= -12.5x + 108; R^2=0.63).
d) Failure wind speed for shoots in wet soil plotted against root lodging index at SB (y= -15.6x + 153; R^2=0.53).

GENERAL CONCLUSIONS

- **More than half of the varieties will have different standing powers for stem and root lodging.**
- One standing power makes a large difference to lodging risk and is the equivalent of significant changes in management, such as a split chlormequat application or 50 fewer plants m^{-2}.
- Varieties with different risks to stem and root lodging should be managed differently to minimise lodging. Root lodging is best reduced by reducing plant establishment and rolling before GS30, whereas stem lodging is best reduced by delaying and reducing fertilizer N.

- Two approaches (A & B) have been developed for measuring separate standing powers for stem and root lodging.

- Approach A involves measuring several plant characteristics then inputting the data into a model of lodging to calculate the risks to stem and root lodging. This approach is very reliable and will require data from 4 trials per year to classify the varieties into 5 significantly different standing powers. This will take 75 person days per year (35 varieties per trial, each replicated twice).
- Approach B involves using a lodging instrument to quickly measure lodging resistance in the field. This approach requires 1-2 person days to measure one trial and was shown to correctly predict lodging at the 2 test sites in 2002. At its current stage of development this represents a significant advance over the present method of scoring natural lodging as and when it occurs in the R.L. trials because it can correctly assign rankings for any site in every season. It will require pilot testing on a range of soil types to prove its ability to identify standing powers for root lodging without irrigation or special crop management. After this it could be used at all R.L. trials to confidently assign standing powers for both stem and root lodging.

APPENDIX 1

Rankings of winter wheat varieties for resistance against root lodging differ from the rankings against stem lodging.

INTRODUCTION

Lodging, the permanent displacement of stems from the vertical, affects all cereal species and is a major limiting factor on grain production worldwide (Gent & Kiyomoto 1998). Lodging is most likely during the 2 or 3 months preceding harvest and occurs through interactions between the plant, wind, rain and soil. Wind exerts a force which bends or breaks the stem base (stem lodging), or displaces the roots within the soil (root lodging). Rain wets the soil to reduce its strength, and increases the load borne by plant structures. Very few observations have been made of the lodging process as it occurs and conjecture exists as to which of the two mechanisms of lodging predominates in winter wheat (*Triticum aestivum* L.). Crook & Ennos (1993) reasoned that root lodging should be the predominant form in modern wheat varieties whereas Neenan & Spencer-Smith (1975) favoured stem lodging. Sterling *et al.* (2003) observed both mechanisms during wind tunnel experiments on field grown winter wheat. Berry *et al.* (2003) showed that the risk of stem lodging increased through grain filling relative to the risk of root lodging because the stem bases become progressively weaker. It thus seems likely that both forms of lodging occur in commercially grown winter wheat in the UK.

The likelihood of either stem or root lodging occurring has been shown to be affected by the environment and crop management. For example, root lodging is more likely in wet soil conditions because the shear strength of the soil is weak, whereas the likelihood of stem lodging increases in soils with high levels of mineral nitrogen because weak stems develop (Berry *et al.* 2000). As regards crop management, high plant populations increase the likelihood of root lodging over stem lodging, whereas early applications of nitrogen fertilizer increase the likelihood of stem lodging over root lodging (Berry *et al.* 2000).

Varieties of winter wheat have large differences in their ability to resist lodging (Easson *et al*. 1993; Crook & Ennos 1994). Breeders have improved lodging resistance by shortening the stems of cereal crops through the introduction of dwarfing genes (*Rht1* and *Rht2*). However, even varieties with the same height often have large differences in standing ability (Table 1), which indicates that other traits must be important in determining lodging risk. Variety differences have been observed for the characteristics which determine stem strength and anchorage strength (Crook & Ennos 1994; Griffin 1998), but no evidence has been presented to show that these stem and anchorage characteristics are linked. If there are no obligate links between these characteristics then susceptibility to stem and root lodging amongst winter wheat varieties may only be weakly correlated. A degree of correlation should probably be expected, regardless of whether the stem and anchorage traits are related, because similar canopy traits determine the wind induced force acting on the stem base and anchorage system. A weak correlation between the two forms of lodging could result in some varieties being resistant to root lodging, but relatively susceptible to stem lodging, and vice-versa. If true, then this would necessitate careful selection of varieties according to the likely environment, and then targeted crop management to improve any specific variety weakness and minimise both types of lodging.

This paper investigates the degree of correlation between the stem and root lodging susceptibilities of winter wheat varieties. This is done by calculating the stem and root lodging risks of 15 varieties using a model of lodging described by Baker *et al.* (1998). This model predicts stem lodging when the base bending moment of a shoot (calculated from the height at centre of gravity, natural frequency and ear area of a shoot) exceeds the failure moment of the stem base (calculated from the diameter, wall width and failure yield stress of the stem). Root lodging is predicted when the sum of the base bending moments of each shoot on a plant exceeds the anchorage strength (calculated from the spread and depth of the root plate). In the following text shoot base bending moment can be approximated to shoot leverage; stem failure moment to stem strength; and anchorage failure moment to anchorage strength.

MATERIALS AND METHODS

Field experiments

Experiments were done at three UK sites: ADAS Rosemaund (52.1°N, 2.5°W) in 1999-00, 2000-01, 2001-02 (RM00, RM01, RM02), ADAS Boxworth (52.2°N, 0.0°W) in 1999-00, 2000-01 (BX00, BX01) and Sutton Bonington (52.5°N, 1.3°W) in 2001-02 (SB02). ADAS Rosemaund has a silt clay loam (Bromyard series), Boxworth has a clay (Hanslope series) and Sutton Bonington has a light medium stony loam (Dunnington Heath series). At each site, fifteen winter wheat varieties (Table 1.1) were grown in 24m x 2m plots arranged in a randomised block design with three replicates. The varieties were introduced between 1986 and 1999 and were chosen to provide a wide spread of lodging resistance, as shown by their standing powers ranging between five (very lodging susceptible) and nine out of nine (Table 1.1). All varieties were semi-dwarfs apart from Cadenza and Mercia. The scores for straw shortness varied between four (very tall) and eight (short) out of nine.

Table 1.1. *Characteristics of the varieties used (Anon. 1994; 1999).*

Variety	Standing power	Straw shortness	Year of introduction
Buster	9	8	1995
Cadenza	6	4	1994
Charger	5	8	1997
Consort	8	8	1995
Equinox	9	9	1997
Harrier	6	8	1998
Hereward	8	7	1990
Hussar	6	7	1992
Madrigal	8	8	1997
Mercia	6	6	1986
Reaper	6	7	1996
Rialto	7	6	1995
Savannah	7	7	1998
Shamrock	8	8	1999
Spark	7	5	1994

- Standing power and straw shortness scores are out of nine, with high scores representing high lodging resistance or short straw.

The experiments were sown at 375 seeds m^{-2} and sowing dates ranged from 3-22 October. The amounts and timings of N fertilizer, applied as granules of ammonium nitrate, were calculated using measurements of soil mineral nitrogen in February and recommendations described in Anon. (2000). At RM02, the crops received a plant growth regulator consisting of New 5C Cycocel (645 g l^{-1} chlormequat + 32 g l^{-1} choline chloride) applied at the 'ear at 1 cm' stage (GS31; Tottman, 1987) followed by Terpal (155 g l^{-1} 2-chloroethylphosphonic acid + 305 g l^{-1} mepiquat chloride) when the flag leaf had fully emerged (GS39).

None of the other crops received a plant growth regulator. Irrigation was applied to the RM and SB sites to induce lodging after the lodging associated plant characters had been measured. A boom irrigator (Briggs Irrigation) was used at RM and an overhead sprinkler system (Access Irrigation Ltd) used at SB. These systems were used to apply up to 25mm water per day during 4 to 8 days between GS75 and GS85. A prophylactic programme of disease, weed and pest control was used for all experiments.

<u>Measurements</u>

Measurements of the plant characters associated with lodging were made during grain filling (GS71 to GS79). Ten plants were selected randomly from one half of each plot, avoiding the outer three rows, and the natural frequency was measured on each main shoot before the plants were excavated with a hand fork to a depth of about 100mm. The intention at sampling was to ensure that the structural crown roots were completely recovered. Laboratory measurements included the spread and depth of the root plate; the number of shoots per plant; the height at centre of gravity and ear area of each main shoot; together with the length, diameter, wall width and breaking strength of the bottom two internodes (internodes 1 and 2). The methods for these measurements are described in detail by Berry *et al.* (2000).

A visual assessment of the percentage area of crop that was lodged at 5^o to 45^o (from the vertical), 45^o to 85^o and 85^o to 90^o was made within the unsampled half of each plot (10m x 2m), including its edges. Lodging index was calculated as 1/3 (% area leaning) + 2/3 (% area lodged) + (% area lodged flat). During lodging assessments, the dominant mechanism and point of failure was identified i.e. whether by stem failure or anchorage failure. Assessments were done after each rain event or irrigation treatment, or weekly during dry periods between ear emergence and harvest.

Calculations

The failure yield stress of the stem wall (σ) was calculated for internodes 1 and 2 using from the breaking strength of the internode (F_s), its length (h), radius (a) and wall width (t).

$$\sigma = \frac{F_S h a}{\pi\left(a^4 - (a-t)^4\right)} \tag{1.1}$$

The stem failure moment (B_S) is calculated from:

$$B_S = \frac{F_S h}{4} \tag{1.2}$$

The shoot base bending moment (B) was obtained from the following expression (Baker *et al.* 1998):

$$B = \frac{1}{2}\rho A C_d X V_g^2 \left(1 + \frac{g}{(2\pi n)^2 X}\right)\left(1 + e^{-\pi\xi}\frac{\sin(\pi/4)}{\pi/4}\right) \qquad (1.3)$$

where ρ is the density of air (1.2 kg m^{-2}), A is the projected ear area, X is the shoot's height at centre of gravity, Vg is the gust speed (ms^{-1}), n is the shoot's natural frequency, g is the acceleration due to gravity (9.81 ms^{-2}), ξ is the shoot's damping ratio (0.08), C_d is the drag coefficient of the ear (1.0) and the remaining symbols take their usual meanings.

The anchorage failure moment (B_R) is calculated from:

$$B_R = k_3 s d^3 \qquad (1.4)$$

where k_3 is taken as 0.43, s is the soil shear strength and d is the root cone diameter. Soil shear strength was calculated using equation 1.5, in which i is the daily rainfall, l is the structural rooting depth, f is the soil moisture content at field capacity, w is the soil moisture content at permanent wilting point, ρ_s is the density of soil and ρ_w is the density of water. S_D and S_W are values for soil shear strength at permanent wilting point and field capacity for which methods of calculation are described in Baker *et al.* (1998).

$$s = s_D - \frac{i}{\frac{\rho_s}{\rho_w}(f - w)\, l}(s_D - s_w) \qquad (1.5)$$

The wind speeds required to buckle internodes 1 (V_{gS1}) and 2 (V_{gS2}) and cause anchorage failure (V_{gR}) were calculated by combining and rearranging equations (1.2) and (1.4), with equation (1.3) (Berry *et al.* 2000):

$$V_{gS1} = \sqrt{\frac{2B_{S1}}{(\rho A C_D X)\left(1 + \frac{g}{(2\pi n)^2 X}\right)\left(1 + e^{-\pi\delta}\frac{\sin(\pi/4)}{\pi/4}\right)}} \qquad (1.6)$$

$$V_{gS2} = \sqrt{\frac{2B_{S2}}{\left(\frac{X - h_1}{X}\right)(\rho A C_D X)\left(1 + \frac{g}{(2\pi n)^2 X}\right)\left(1 + e^{-\pi\delta}\frac{\sin(\pi/4)}{\pi/4}\right)}} \qquad (1.7)$$

$$V_{gR} = \sqrt{\frac{2B_R}{N(\rho A C_D X)\left(1 + \frac{g}{(2\pi n)^2 X}\right)\left(1 + e^{-\pi\delta}\frac{\sin(\pi/4)}{\pi/4}\right)}} \qquad (1.8)$$

where B_{S1} and B_{S2} represent the failure moments of internodes 1 and 2 respectively, h_1 represents the length of internode 1 and N represents the number of shoots per plant.

Statistical analysis

Analysis of variance procedures within Genstat 6 (Payne 2002) for fully randomised split plot designs were used to test for differences among treatments and calculate standard errors of differences between means. The six site/seasons formed the main plots and the replicate plots within them, each containing a single variety, the sub plots. In the cases where two types of lodging were compared within the same sub plot, the analysis was treated as a split-split plot and lodging type considered as a sub-subplot factor. For the calculated failure-wind speeds-to-cause-lodging, this split-split plot analysis was used to test for interactions between variety and the type of lodging (stem or root).

RESULTS

The average number of plants established after winter varied between 201 plants m^{-2} at BX00 to 282 plants m^{-2} at RM02 and SB02. Significant differences were observed between varieties for the RM00 ($P<0.05$), RM01 ($P<0.01$), RM02 ($P<0.001$) and SB02 ($P<0.001$) site/seasons. Differences from the mean were only greater than +/- 50 plants m^{-2} at SB02, where Reaper and Charger were about 80 plants m^{-2} more than the site mean, whereas Spark and Madrigal were about 70 plants m^{-2} less. Cadenza failed to emerge at BX00 and RM00, cv Harrier failed to emerge at RM02 and SB02 and cv Madrigal had very poor emergence at RM01 Measurements were not taken on these plots as a result of this. In February, the soil mineral N in the top 90cm of soil averaged 71 kg ha^{-1} across the six site/seasons, ranging from 55 kg ha^{-1} at BX01 to 95 kg ha^{-1} at RM01 kg ha^{-1}.

Observed lodging and calculated failure wind speeds

Both root and stem lodging were observed in the field experiments. Root lodging was the predominant form at BX00, BX01, RM01 and SB02, with stem lodging more common at RM00 and RM02. Across all site/seasons, root lodging varied from 2% for Hereward to 47% for Cadenza. Stem lodging varied from 0% for Consort to 19% for Cadenza. Crop management was designed to produce a low lodging risk to enable the plant characteristics associated with lodging to be measured on unlodged plants. Nonetheless, late season lodging, caused by natural weather events or through irrigation, resulted in enough lodging to test the model's calculations of root and stem lodging risks. Fig. 1.1 shows that the calculations of both stem and root failure wind speeds correlate well with the observations of lodging, which gives further confidence that the model's output is a reliable indicator of lodging risk. The stem failure wind speed was calculated from either internode 1 or internode 2 depending on which failed first. Internode 2 was the most common point of stem failure at BX00, RM00 and SB02, whereas internode 1 failure was more common at RM01 and RM02, with both internodes equally likely to fail at BX01. Across all sites and seasons, internode 2 was calculated to fail first in 61% of the plots.

The observed lodging illustrates two reasons why the authors have used calculations of failure wind speed to investigate differences between varieties in the mechanism of lodging rather than relying on observations of lodging. Firstly, stem and root lodging rarely occurred within the same experiment. Secondly, it was difficult to distinguish the lodging risks of lodging resistant varieties. This is illustrated by the cluster of varieties with negligible amounts of lodging in Fig. 1.1.

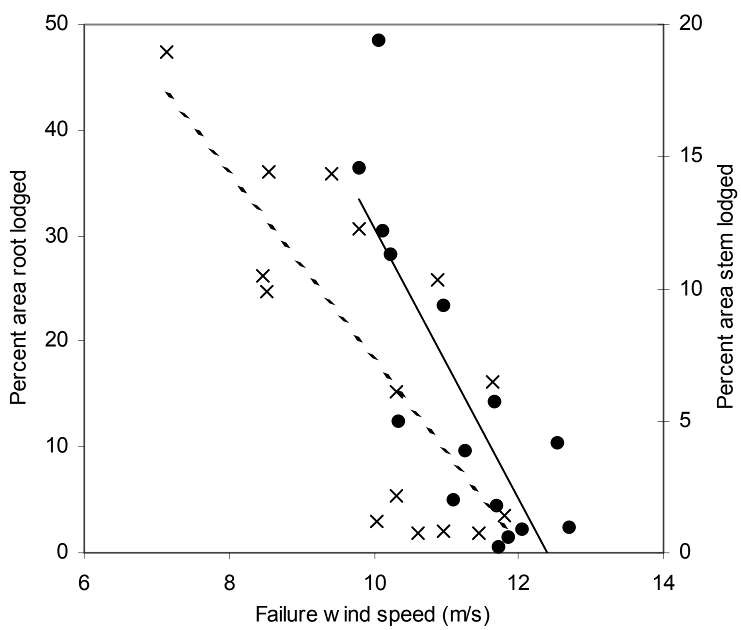

Fig. 1.1. Root failure wind speed plotted against percentage area of root lodging (×, R^2=0.60, P<0.001); Stem failure wind speed plotted against percentage area of stem lodging (•, R^2=0.65, P<0.001). All data are varietal means across the six site seasons.

An ANOVA was carried out to investigate how site/season, variety and type of lodging (stem or root) affected the failure wind speed. The analysis showed significant differences between site/seasons, type of failure and a strong interaction between these factors (Fig. 1.2; P<0.001). The root and stem failure wind speeds varied from 7 and 8 ms^{-1} (respectively) to 14 ms^{-1} (for both) for the different sites and seasons (Fig. 1.2). This was surprising considering that all crops received similar management and suggests that soil type and weather conditions during crop growth have a large influence on lodging risk. The strong interaction shows that sites and seasons affect the stem and root failure wind speeds by different amounts. For example, the average stem failure wind speed was 3.4 ms^{-1} greater than the average root failure wind speed at RM00 and 2.4 ms^{-1} less at SB02. These observations confirm that the balance between stem and root lodging risk can be altered in different environments.

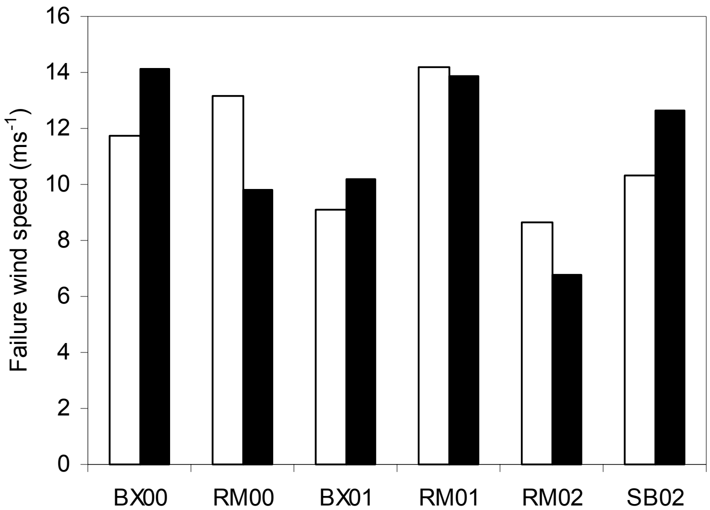

Fig. 1.2. Average stem failure wind speed (open bars) and root failure wind speed (closed bars) for each site season. Interaction SED = 0.833 ms^{-1} (15 df).

The variety differences in failure wind speed were highly significant ($P<0.001$), but there was a slight interaction between site/season and variety ($P<0.05$) Further analysis of this interaction showed that it was caused by four varieties behaving inconsistently. For each of these varieties, the inconsistencies occurred within a single site season. Due to the low level of significance of this interaction compared with the main effects, and the small effects on the mean failure wind speed of the varieties, the mean stem and root failure wind speeds of the varieties across the sites and seasons are presented (Fig. 1.3). Importantly the ANOVA also showed a significant interaction between variety and type of failure ($P<0.001$) and there was no interaction between site-season, variety and type of failure. This occurred because the variety rankings for stem failure wind speed differed from the rankings for the root failure wind speeds. It shows that at least some of these differences in rankings must be statistically significant and importantly these differences were consistent across the sites and seasons.

Fig. 1.3 shows that the root and stem failure wind speeds were positively correlated ($P<0.05$), but a linear regression only accounted for 33% of the variation between the two parameters. On average, the stem failure wind speed was 1.2 ms^{-1} greater than the root failure wind speed. Varieties which deviate significantly from this will have different rankings for stem and root lodging resistance. Therefore varieties lying significantly above the line in Fig. 1.3 will be ranked higher for root lodging resistance than for stem lodging resistance and vice versa for varieties lying below this line. Varieties with a greater resistance against root lodging (compared with stem lodging) include Savannah (P<0.05), Rialto, Buster and Hereward (P<0.10). Varieties with a greater resistance against stem lodging resistance include Cadenza, Spark (P<0.05) and Mercia (P<0.10).

These findings are supported by the observations of stem and root lodging. The three varieties predicted in Fig. 1.3 to be more resistant to stem lodging had rankings for observations of stem lodging (least lodging first) of 6, 10 and 15 (average 10). This average ranking increased to 13 for observations of root lodging in the same set of varieties. For the varieties predicted to be more resistant to root lodging, the average ranking increased from 5 for root lodging to 6 for stem lodging. The latter comparison included two varieties for which only small amounts of lodging were observed which probably limited any change in ranking.

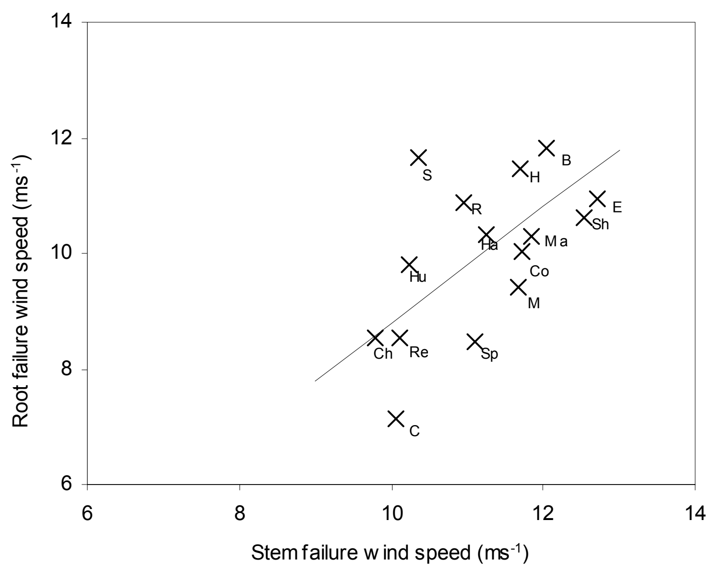

Fig. 1.3. Stem failure wind speed plotted against root failure wind speed for 15 winter wheat varieties; B-Buster, C-Cadenza, Ch-Charger, Co-Consort, E-Equinox, Ha-Harrier, H-Hereward, Hu-Hussar, Ma-Madrigal, M-Mercia, Re-Reaper, R-Rialto, S-Savannah, Sh-Shamrock, Sp-Spark. The mean difference between the stem and root failure wind speeds is represented by y= x –1.2 (—). The SED for the interaction between type of failure and variety = 0.594 ms^{-1} (162 df).

The probabilities of stem and root lodging can be estimated from the failure wind speeds using Fig. 1.4. The solid line shows that there is a probability of greater than 0.9 of experiencing a wind speed of at least $10ms^{-1}$, which drops to less than 0.1 for a wind speed of at least 17 ms^{-1}. This relationship can be used to estimate the chance of experiencing stem failure wind speeds. For root lodging to occur it is assumed that at least 7mm rain must fall to weaken the soil in addition to experiencing the root failure wind speed. The dashed line in

Fig. 1.4 illustrates the probability of experiencing both rain and wind events on the same day. More details of how the probabilities for Fig. 1.4 were calculated are described in Berry *et al.* (2003). The stem failure wind speeds illustrated in Fig. 1.3 range from about 10 ms^{-1} to 13 ms^{-1}, which equates to lodging probabilities of 0.9 to 0.5. The root failure wind speeds range from about 7 ms^{-1} to 12 ms^{-1}, which equates to lodging probabilities of 0.7 to 0.1. More root lodging than stem lodging was observed in the experiments because irrigation was used to weaken the soil. Fig. 1.4 illustrates how small changes to failure wind speed can make a large difference to the probability of lodging.

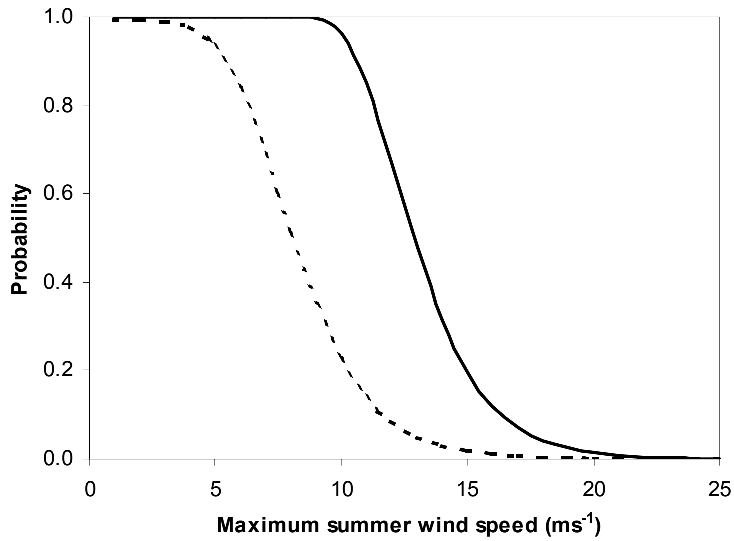

Fig. 1.4. Probabilities of experiencing wind gusts independent of rainfall (—) and wind gusts with ≥7 mm daily rain (---) between mid June and mid August within the main wheat growing regions of the UK. From Berry *et al.* (2003).

Significant differences were observed between the varieties for all of the lodging associated plant characters ($P<0.05$). An analysis of the range of each plant character in a wide range of breeding material together with an assessment of their impact on lodging risk (as in Berry *et al*., 2003) would indicate which traits breeders should select for to realize the greatest increase in lodging resistance. Several pairs of traits were linked, but importantly no correlations were detected between the plant characters that determine the strength of the stem base and the anchorage system. This helps explain why the variety susceptibilities towards stem and root lodging were not well correlated.

DISCUSSION

We have shown that the susceptibilities of 15 winter wheat varieties to stem and root lodging were not well correlated. Several of the varieties had significantly different rankings for the wind speeds required for the two types of lodging. This was because the plant characters that determine stem strength were not linked with the characters that determine anchorage strength. It is important now to assess whether the differences in the susceptibility towards stem and root lodging for individual varieties are large enough to necessitate the use of separate crop management strategies to minimise both types of lodging. To answer this question the following section outlines a method for classifying the root and stem lodging resistances of varieties. The implications of these classifications for wheat management are then considered.

It is not possible to state absolute values for stem and root failure wind speeds of different varieties because they are affected by environmental conditions. However, this study has shown that the differences in failure wind speed between varieties are consistent between sites and seasons, so it is possible to present these. This information has been calculated for each variety at each site as its deviation from the failure wind speed of Charger and the mean values over all site seasons are given in Table 1.2. Charger was chosen because it has a similar ranking for both stem and root lodging. In order to classify the varieties we have assumed that Charger has a standing power of 5 for both stem and root lodging and the most resistant variety for either stem or root lodging has a standing power of 9. This means that each standing power classification should span about 0.8 ms^{-1} for both stem and root lodging. Finally, we assume that Charger is in the middle of its standing power classification which means that a standing power of 5 ranges from –0.4 ms^{-1} to +0.4 ms^{-1}. Other standing power classifications can then be calculated based on an interval of 0.8 ms^{-1}. Table 1.2 shows that 10 of the 15 varieties have different standing powers for stem and root lodging. Five of these have differences of at least two standing powers.

Table 1.2. *A method for classifying stem and root lodging*

Variety	Stem lodging: Failure wind speed deviation from Charger (ms^{-1})	Stem lodging: Classification for stem lodging (1-9)[a]	Stem lodging: Probability (P) of lodging when P=0.1 for the most resistant variety	Root lodging: Failure wind speed deviation from Charger (ms^{-1})	Root lodging: Classification for root lodging (1-9)[a]	Root lodging: Probability (P) of lodging when P=0.1 for the most resistant variety
Buster	2.26	8	0.14	3.28	9	0.10
Cadenza	0.28	5	0.35	-1.38	3	0.68
Charger	0.00	5	0.39	0.00	5	0.44
Consort	1.92	7	0.16	1.51	7	0.23
Equinox	2.92	9	0.10	2.42	8	0.15
Harrier	1.46	7	0.20	1.78	7	0.21
Hereward	1.90	7	0.16	2.92	9	0.12
Hussar	0.45	6	0.32	1.26	7	0.26
Madrigal	2.06	8	0.15	1.77	7	0.21
Mercia	1.87	7	0.17	0.90	6	0.31
Reaper	0.33	5	0.34	0.02	5	0.44
Rialto	1.17	6	0.23	2.36	8	0.16
Savannah	0.56	6	0.31	3.12	9	0.11
Shamrock	2.74	8	0.11	2.09	8	0.18
Spark	1.31	7	0.22	-0.02	5	0.45
SED (18 reps 151 df)	0.285			0.724		
LSD (5%)	0.563			1.430		

[a] A standing power of 3 ranges from -2.0 to -1.2 ms^{-1}, 4 (-1.2 to -0.4 ms^{-1}), 5 (-0.4 to 0.4 ms^{-1}), 6 (0.4 to 1.2 ms^{-1}), 7 (1.2 to 2.0 ms^{-1}), 8 (2.0 to 2.8 ms^{-1}), 9 (>2.8 ms^{-1}).

How these classifications for stem and root lodging relate to probabilities of lodging depends upon how the crop has been managed and how the weather affected its growth. If we assume that the most resistant variety has a 10% chance of lodging then the lodging probabilities can be estimated for the other varieties using Fig. 1.4. This demonstrates that some varieties have large differences in their probabilities for stem and root lodging when the most resistant varieties within an experiment have identical risks to stem and root lodging. For example, the stem and root lodging probabilities for Savannah are estimated to be 0.31 and 0.11 respectively, demonstrating that this variety is three times as likely to stem lodge. Spark, Cadenza and Mercia have around two-fold differences and are more likely to root lodge.

Separating the standing powers by a failure wind speed of 0.8 ms^{-1} means that the standing powers would be significantly different for stem lodging because the LSD for the stem failure wind speeds is 0.56 ms^{-1} (Table 1.2). However, this would not be the case for the root lodging standing powers because the LSD for the root failure wind speed is 1.43 ms^{-1}. For the root lodging standing powers to be significantly different ($P<0.05$), the SED for root failure wind speed must to be reduced from 0.724 to about 0.4 ms^{-1}. The number of plots (n) required for this can be estimated using:

$$SED = \sqrt{\frac{2 \times residual \cdot mean \cdot square}{n}} \qquad (9.1)$$

This indicates that the number of plots used in this study must be trebled to about 800 for the reduction in the SED which would be required for five significantly different classifications for root lodging resistance. This could be achieved after three years by growing 5 trials per year, each with 35 varieties replicated twice. In the current Recommended Lists, the LSD for standing power is 1.5 times the size of one standing power interval. If this criterion is used then only 360 plots would be required.

We chose to calculate the failure wind speed deviations from a single variety rather than from the mean of all varieties because the latter method could allow the average lodging resistance to fall if new varieties introduced have a lower than average lodging resistance. This would not be easy to detect if it occurred gradually over several years. Therefore, it would be better to calculate the differences on one or more standard varieties. It would probably be safest to use two or three standard varieties. It is unlikely that the same standard varieties could be used in a testing system indefinitely because break down to diseases could affect their lodging resistance. Therefore they would need replacing periodically with newer varieties with similar lodging resistances.

The effects of management decisions on lodging risks have been quantified by Berry *et al.* (2000; 2002). These findings have recently been adjusted to account for better specified aerodynamic characteristics of the shoot (Sterling *et al.* 2003). We have presented these management effects on lodging risk in terms of their effect on the standing powers for stem and root lodging (Table 1.3). This shows that root lodging resistance is improved by the equivalent of a single standing power by reducing plant establishment by about 50 plants m^{-2} (between 400 and 200 plants m^{-2}). Our unpublished data indicates that this trend continues below 200 plants m^{-2}. Rolling the soil in the spring would be expected increase the standing power for root lodging by one. Resistance to stem lodging is reduced by two standing powers by sowing on soil with about 30 kg ha^{-1} more residual N. This effect would be almost reversed by reducing and delaying fertilizer N to target a green area index of 5. Both types of lodging resistance are improved by between one and two standing powers with a split application of chlormequat. Delaying drilling by 2 weeks would raise both standing powers by one. Thus it is clear that a change by one standing power is equivalent to significant changes in crop management. Therefore, the varieties with different standing powers for stem and root lodging will benefit from appropriate management to prevent excessive susceptibility to either type of lodging.

Table 1.3. Effect of crop management on the standing powers for stem and root lodging.

Factor	Change to husbandry	Change in standing power for STEM lodging	Change in standing power for ROOT lodging
Soil residual N in spring	Increase by 30 kg N ha^{-1}	-2	-1
Sowing date	Per week delay	+0.5	+0.5
Plants m^{-2}	Per 50 plants m^{-2} reduction	+0.5	+1
PGRs	Split chormequat	+1 to +2	+1 to +2
Fertiliser N	Reduce and delay (target GAI 5)	+1.5	+1
Spring rolling	Pre-GS30	0	+1

APPENDIX 2

Methods for rapidly measuring the lodging resistance of wheat varieties.

INTRODUCTION

The flattening of cereal crops, known as lodging, can cause large reductions in grain yield and quality (Berry *et al*. 1998). The principal method by which growers minimise lodging is through the use of lodging resistant varieties. Lodging can also be minimised by delayed sowing, sowing fewer seeds, reducing and delaying applications of fertilizer and by applying plant growth regulators (Berry *et al.* 2000). Two types of lodging exist. Root lodging occurs when the anchorage of the root/soil system fails. Stem lodging occurs when the stem base buckles. There is conjecture about which type predominates with Crook & Ennos (1993) favouring root lodging and Neenan & Spencer-Smith (1975) reasoning that stem lodging is more common. Recently it has been shown that winter wheat varieties have different rankings to root and stem lodging (Berry *et al.* 2002). This finding should affect the way in which lodging risk is minimised because different crop management is required to reduce root lodging compared with that required to reduce stem lodging (Berry *et al.* 2000). For example, the risk of root lodging is reduced most effectively by establishing fewer plants, whereas stem lodging is best reduced by delaying and reducing nitrogen fertilizer.

Variety testers in the UK use observations of lodging to rank varieties for lodging resistance on a scale from 1 to 9 (9 being the most resistant). This method has been a valuable way of assessing lodging for many years, but it does have two short-comings. Firstly, it is reliant on lodging events occurring within the variety trials. These do not occur in significant amounts in most years, which means that lodging prone varieties are not always identified until they are grown on a large scale. It is also difficult to assign the correct ranking to resistant varieties when little lodging occurs. Secondly, it does not account for the different risks to stem and root lodging because the mechanism of lodging is not identified when the amount of lodging is assessed. This means that the lodging rankings are a combination of stem and root lodging. In order to assess both types of lodging the variety testers could begin to record the type of lodging. However this is almost impossible in a severely lodged crop and would require assessments immediately after lodging which are impractical. The methods used by Berry *et al.* (2002) to calculate stem and root lodging risks do not rely on lodging events, but are time consuming because they necessitate sampling and measurement of the stems and roots. Therefore, it is clear that a rapid method of assessing stem and root lodging resistance is required which does not rely upon the occurrence of lodging.

Crook & Ennos (2000) have described a field based method for quantifying lodging resistance which measures the anchorage and stem failure moments and the self weight moment of the shoot. These measurements were then combined to estimate safety factors towards root and stem lodging. This showed that the root and stem lodging resistances of winter wheat cv Consort were greater than cv Soissons. This is in agreement with the Recommended List rankings for combined stem and root lodging resistance (Anon., 1999), but the results were not confirmed by observations of stem and root lodging. Whilst this method was reasonably rapid, it is based on individual plants which means that the test must be repeated many times. Another potential short-coming was the use of self weight moment of the shoot as an indicator of the force exerted on the plant base. This does not account for the interaction between the wind and shoot. Baker *et al.* (1998) showed that base bending moment of a shoot is determined by several factors, including the wind speed acting upon the ear, the area and drag of the ear, together with the height at centre of gravity and natural frequency of the shoot. Other methods for rapidly measuring lodging resistance in cereals include estimating root lodging resistance in rice (Terashima *et al.* 1992) and maize (Fouere *et al.* 1995) from measurements of pushing resistance. Root lodging resistance in maize has also been estimated from the force required to pull roots out of the ground (Beck *et al.* 1987). These methods had mixed amounts of success, assessed only one form of lodging and appear to be too time-consuming to enable large numbers of varieties to be tested economically.

This paper describes the development and testing of two methods for rapidly assessing both the root and stem lodging resistance of winter wheat varieties grown in field plots using an instrument designed to lodge plants. The criteria are for the procedure to predict differences in lodging between wheat varieties, take no longer than five minutes per plot and ideally to separate root and stem lodging resistance. The next section outlines how the methods and instruments were developed, followed by a description of the test crops and protocols used. The results of the tests are presented and discussed in the final sections. In the following text shoot base bending moment can be approximated to shoot leverage; stem failure moment to stem strength; and anchorage failure moment to anchorage strength.

DEVELOPMENT OF METHODS

Two methods were developed to estimate the risk to stem and root lodging which were based on the following principles;

Stem lodging occurs when the wind induced base bending moment of a shoot > stem failure moment
Root lodging occurs when the wind induced base bending moment of the shoots > anchorage failure moment

Both methods used a lodging instrument (described below) in which the force required to cause stem or anchorage failure was estimated from the maximum resisting force offered by cereal stems as they were pushed (rotated) away from their vertical position. The force required to rotate shoots typically increases as the angle of rotation becomes greater, before falling rapidly after either the stem base or the anchorage system fails. It was anticipated that stem failure would be induced when the soil was dry and strong, and anchorage failure would be induced when the soil was wet and weak. This is because wetting the soil from permanent wilting point to field capacity reduces its shear strength by several fold (Griffin 1998). Method 1 attempted to account for both the base bending and failure moments with a single 'pushing' test that measured the maximum resisting force of whole shoots as they were rotated from the vertical. Varietal differences in the base bending moment were accounted for by adjusting the height at which the shoots were pushed. Method 2 measured the stem failure, anchorage failure and base bending moments separately, then used these measurements to calculate the resistances to stem and root lodging in terms of the wind speeds needed to cause failure. This method involved the removal of the top half of the shoots, to eradicate the influence of the base bending moment, then measured the stem and anchorage failure moments on the remaining stubble. The base bending moment of the shoot was calculated from measurements of the ear area, height at centre of gravity and natural frequency of the shoots. Method 2 was more time consuming to carry out than Method 1, but it is potentially more accurate because its calculation of base bending moment accounts for the way in which the shoot interacts with the wind.

Lodging instrument

During 2000, several types of instrumentation for measuring the force required to displace cereal shoots were considered. The pros and cons of automating the device were weighed, i.e. whether it should be tractor mounted or have a mechanically operated pushing arm. It was concluded that a manually operated device should be developed that would not require skilled operators and which could be reproduced cheaply. The main criteria was that it should 1) measure the lodging resistance of several dozen shoots simultaneously, 2) have an adjustable pushing bar height, 3) be portable within the field and 4) be easily dismantled for transport between sites.

A diagram of the instrument used to measure lodging resistance is shown in Fig. 2.1. The base frame, upright struts and rotating handles were made from mild steel, while the pushing bar was made from a lighter alloy. The lodging instrument was portable and was manually positioned in front of the wheat to be tested. Then the handles were raised in increments and the force on the pushing bar recorded at each step. The height of the pushing bar was adjustable between 200mm and 1000mm. This could displace the wheat shoots by up to 85^{o} from the vertical. The pushing bar could be locked in position at 5^{o} intervals. A Smart 200N Load Cell (Mecmesin) was used to measure the resisting force offered by the wheat shoots on the pushing bar. This force was registered in N on the digital display of an Advanced Force and Torque Indicator (Mecmesin). Finally, the upright struts and rotating handles could be easily detached from the base frame to facilitate transportation.

Tests in 2001 investigated the most accurate and efficient procedure for identifying the variety differences. This involved testing different numbers of rows, angles and orientations of displacement and the duration of each test on a subset of five varieties grown at Sutton Bonington. In 2002, the best procedure identified in 2001 was used to test Methods 1 and 2 on 14 varieties grown at ADAS Rosemaund and Sutton Bonington. These field experiments are described in the next section.

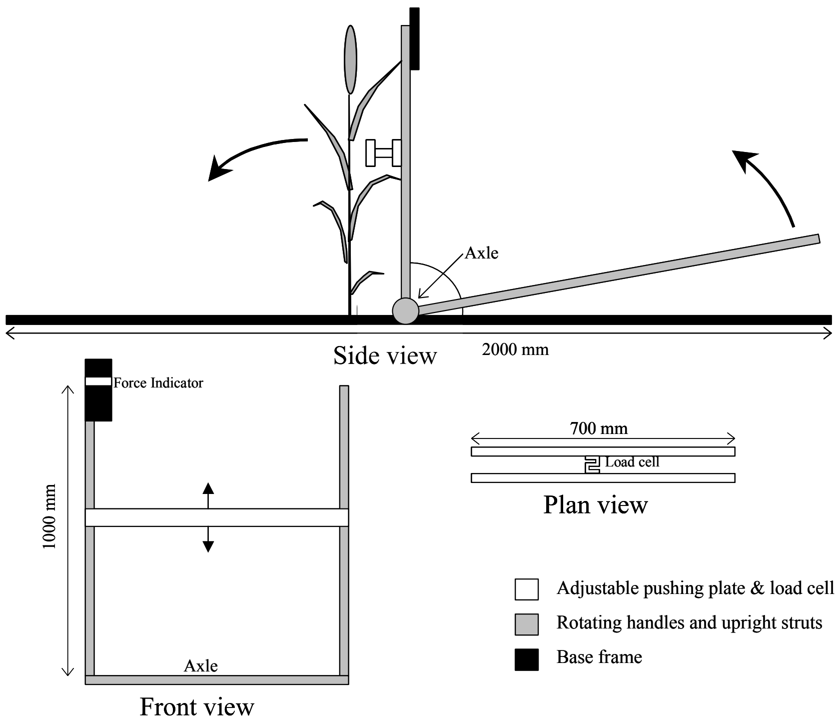

Fig. 2.1. Diagrams of the lodging instrument from the side, front and top.

Method 1

This section calculates the height up the shoot at which the rotating force should be applied to best account for the differences in base bending moment of the shoot.

A rapid estimate of the base bending moment of a shoot is difficult because it is determined by several plant characteristics, and these are time-consuming to measure. Baker (1995) showed that the base bending moment of a shoot is strongly influenced by its height and it is possible to predict its effect on base bending moment via several steps. Berry (1998) showed that height is linearly related with height at centre of gravity, which in turn is related to the natural frequency of a shoot via the non-linear relationship described by Berry *et al*. (2000). Height at centre of gravity and natural frequency can then be used to calculate base bending moment using equation 2.1 described in Baker *et al*. (1998).

$$B = \frac{1}{2}\rho A C_d X V_g^2 \left(1 + \frac{g}{(2\pi n)^2 X}\right)\left(1 + e^{-\pi\xi}\frac{\sin(\pi/4)}{\pi/4}\right) \tag{2.1}$$

where ρ is the density of air (1.2 kg m^{-3}), A is the projected ear area (m^{-2}), X is the shoot's centre of gravity (m), V is the gust speed (ms^{-1}), n is the shoot's natural frequency (Hz), g is the acceleration due to gravity (9.81 ms^{-2}), ξ is the shoot's damping ratio and C_d is the drag coefficient of the ear.

Combining the findings of Berry (1998) and Berry *et al.* (2000) shows that $n \propto h^{-1.5}$, where h is the height of a shoot. By using equation (2.1) it can be shown that the base bending moment is proportional to the cube of shoot height. This means that to account for the greater bending moment of a tall variety, the pushing height must be raised so that the force to displace the stems is reduced by an amount which is proportional to the cube of shoot height. The adjustments to pushing height must also minimise changes in the amount that the ear is deflected because this affects the self weight moment of the shoot. Using the engineer's theory of bending (Rees 1990) it can be shown that the force (F) required to deflect the ear of a shoot by a given amount (d) is given by:

$$F = 2EI\frac{d}{\alpha^2 h^3 \left(1 - \alpha/3\right)} \tag{2.2}$$

Where α is the ratio between x and h, x is the distance from the base of the plant to the point where the force is applied, and E and I are the Young's modulus and second moment of area of the stem respectively. This shows that if the pushing force is applied at a constant proportion of the crop height (α) then the force required to deflect the shoot by a given amount will be proportional to the inverse of the height cubed. This is very convenient because it means that applying the force at a constant value of α should account for the height related differences in base bending moment, while at the same time allowing any differences in ear weight to contribute. A value for α of 0.5 was chosen in order to minimise the error caused by pushing too low, while also pushing at a position where the stems are reasonably stiff. Easson *et al.* (1992) showed that the top half of wheat stems are much more flexible than the bottom half.

Method 2

This method includes a more sophisticated consideration of the dynamic interaction of the wind with the shoot. Sterling *et al.* (2003) showed that the wind speed required to cause stem lodging (V_{gS}) and root lodging (V_{gR}) can be calculated using equations 2.3 and 2.4.

$$V_{gS} = \sqrt{\frac{2B_S}{(\rho AC_D X)\left(1+\frac{g}{(2\pi n)^2 X}\right)\left(1+e^{-\pi\delta}\frac{\sin(\pi/4)}{\pi/4}\right)}} \quad (2.3)$$

$$V_{gR} = \sqrt{\frac{2B_R}{N(\rho AC_D X)\left(1+\frac{g}{(2\pi n)^2 X}\right)\left(1+e^{-\pi\delta}\frac{\sin(\pi/4)}{\pi/4}\right)}} \quad (2.4)$$

In these equations B_S and B_R represent the stem base and anchorage failure moments respectively and the other terms are explained after equation 2.1. B_S and B_R can be measured in the field by recording the maximum resisting force as the cereal stems are rotated in dry and wet soil respectively. To do this the upper portion of the shoot must be removed and the pushing force applied at a constant height above ground level. The lower portion of the stem has been shown to be reasonably stiff (Easson *et al.* 1992), so it should be appropriate to estimate the base bending moment (Nm) from the product of the force applied (N) and the height above ground that the force was applied (m).

Rapidly measuring the terms in the denominator of equations 2.3 and 2.4 present a more difficult problem. Sterling *et al.* (2003) has shown that drag coefficient and damping ratio do not deviate much from values of 1 and 0.08 respectively within a range of crop types. Therefore, the critical plant characters that must be measured are the height at centre of gravity, natural frequency of the shoot and the area of the ear.

MATERIALS AND METHODS

Field experiments

Experiments were done at two UK sites: ADAS Rosemaund (52.1°N, 2.5°W) and Sutton Bonington (52.5°N, 1.3°W). ADAS Rosemaund (RM) has a silt clay loam (Bromyard series) and Sutton Bonington (SB) has a light medium stony loam (Dunnington Heath series). In 2000-2001, five winter wheat varieties; Buster, Charger, Harrier, Mercia and Savannah, were grown at SB in 24m x 2m plots arranged in a randomised block design with six replicates. This experiment was used for investigating the best procedures for using the lodging instrument. In 2001-2002, fourteen winter wheat varieties (Table 1.1, not including Harrier) were grown at RM and SB in 24m x 2m plots arranged in a randomised block design with three replicates. The varieties were introduced between 1986 and 1999 and were chosen to provide a wide spread of lodging resistance, as shown by their standing powers ranging between five (very lodging susceptible) and nine out of nine (Table 1.1). The scores for straw shortness varied between four (very tall) and eight out of nine. These experiments were used to test Methods 1 and 2.

The experiments were sown on 3 October at RM and 17 October at SB, both at 375 seeds m^{-2}. The amounts and timings of nitrogen fertilizer, applied as granules of ammonium nitrate, were calculated using measurements of soil mineral nitrogen in February and recommendations described in Anon. (2000). This meant that the experiments received about 220 kg N ha^{-1}. The crops at RM received a plant growth regulator consisting of New 5C Cycocel (645 g l^{-1} chlormequat + 32 g l^{-1} choline chloride) applied at the 'ear at 1 cm' stage (GS31; Tottman, 1987) followed by Terpal (155 g l^{-1} 2-chloroethylphosphonic acid + 305 g l^{-1} mepiquat chloride) when the flag leaf had fully emerged (GS39). The crops grown at SB did not receive a plant growth regulator. Irrigation was applied to the RM and SB sites to wet and weaken the soil. A boom irrigator (Briggs Irrigation) was used at RM and an overhead sprinkler system (Access Irrigation Ltd.) used at SB. These systems were used to apply up to 25mm water per day on between 4 and 8 days between GS75 and GS85. A prophylactic programme of disease, weed and pest control was used for all experiments.

Measurements

Five plant measurements were done on ten shoots chosen randomly from an area of the crop not to be tested with the lodging instrument. The time taken for each shoot to complete three oscillations was recorded. This was converted into the number of oscillations per second (Hz), known as natural frequency. Height to the ear tip was measured, then the shoot was chopped off at ground level and its height at centre of gravity and ear length recorded. The projected area of each ear was measured with an image analyser (Delta-T devices, Cambridge, UK).

The 5th row from the same edge of all the plots was tested with the lodging instrument. The shoots in all the other rows were chopped off at ground level and discarded. The number of shoots to be pushed was counted at the beginning of each test. The resisting force was measured at 20°, 40° and then every 5° up to 80° displacement from the vertical. The pushing bar was held at each angle for 30 seconds to allow the resisting force to stabilize. The number of shoots whose stem base had buckled was counted at each angle of displacement. Whether or not the shoots had been permanently displaced was recorded after each test. Two variations of this procedure were carried out on each plot. Method 1: the pushing height was adjusted to 50% of crop height. Method 2: the shoots were chopped off 500 mm above the soil surface and pushed at 400 mm height.

Soil shear strength (kNm^{-2}) was measured at a depth of 40mm during each test using a hand held shear vane (Pilcon). Five measurements were taken from each of three randomly chosen plots at the beginning, middle and end of each block. Soil trapped in the wings of the shear vane was collected and stored in air-tight bags for determination of the moisture content of the soil.

A visual assessment of the percentage area of crop that was leaning (5^o to 45^o from the vertical), lodged (45^o to 85^o) and lodged flat (85^o to 90^o) was made within the unsampled half of each plot (10m x 2m), including its edges. These observations were converted into a lodging index using the following formula: Lodging index = 1/3 (% area leaning) + 2/3 (% area lodged) + (% area lodged flat). During lodging assessments, the dominant mechanism and point of failure was identified i.e. whether by stem failure or anchorage failure. Assessments were done after each rain event or irrigation treatment, or weekly during dry periods between ear emergence and harvest.

Statistical analyses

Analysis of variance procedures for fully randomised plot and split-plot designs were used within Genstat 6.0 software (Lane and Payne, 1996) to calculate standard errors of differences between means (SED) and significant differences between treatments. Variety formed the main plots and soil wetness (dry or wet) formed the sub-plots. A critical exponential curve was fitted to the angle of shoot rotation against the resisting force measured in each plot. Differentiation was then used to estimate the maximum resistance and the angle of rotation at which it occurred.

RESULTS

Development of procedures for the lodging instrument

In 2001, the most accurate and efficient procedures for identifying the variety differences were investigated. This showed that the lodging instrument best predicted the lodging risk when it displaced and lodged an isolated row of wheat plants. Testing more than one row caused the plants in the first row to be supported by the plants in neighbouring rows. As a result these tests measured resistance to stem bending rather than the failure moment. Failure of a single row usually occurred when the shoots were displaced by between 40^o and 70^o past the vertical. Carrying out the tests at 90^o to or parallel with the direction of drilling made little difference to the predictive ability of the lodging instrument. Pausing at each angle of displacement for 30 seconds or 60 seconds also made little difference.

Testing the lodging instrument

The average number of plants established after winter was 277 plants m^{-2} at RM and 292 plants m^{-2} at SB. Significant differences in plant establishment were observed between the varieties at both sites ($P<0.001$). These differences only exceeded +/- 50 plants m^{-2} at SB where Reaper and Charger were about 80 plants m^{-2} more than the site mean, whereas Spark and Madrigal were about 70 plants m^{-2} less. In February, the soil mineral N in the top 90cm soil was 84 kg N ha^{-1} at RM and 56 kg N ha^{-1} at SB. At RM, stem lodging was caused by natural weather events from early grain filling (GS71) onwards. At SB, root lodging was induced by irrigation from late grain filling (GS77) onwards. Significant differences were observed between the lodging indices of the varieties (P<0.001). The lodging index data was not significantly skewed, so was not transformed for this analysis. Table 2.1 shows that the lodging indices ranged from 1 to 74% at RM and from 1 to 60% at SB.

Table 2.1. *Lodging indices observed at the experimental sites.*

Variety	Index of stem lodging at RM (%)	Index of root lodging at SB (%)
Buster	5	2
Cadenza	74	36
Charger	54	60
Consort	1	7
Equinox	2	1
Hereward	9	1
Hussar	48	44
Madrigal	2	9
Mercia	23	22
Reaper	37	51
Rialto	27	33
Savannah	29	29
Shamrock	24	4
Spark	1	7
Mean	23	20
SED (26 df)	14.4 (***)	10.6 (***)

*** (P<0.001)

The lodging instrument was tested between 28 June and 11 July, which coincided with the grain filling period (GS71-77) (Table 2.2). Irrigation increased the moisture content of the soils and significantly reduced the shear strength of the top 40 mm of soil by about 60% (Table 2.2). The sandy loam at SB was wetted to approximately field capacity. The silt clay loam at RM reached approximately 80% of field capacity, which is estimated at 0.27 g g^{-1}. At both sites, the crop heights ranged from 0.80m for Equinox to 1.02 m for Cadenza. This meant that the height at which the pushing force was imposed during Method 1 ranged from 0.40m to 0.51m above the ground. Experiments to induce lodging under dry soil conditions caused 80 to 100% of the stems to buckle close to the soil surface. Tests under wet soil conditions caused, on average, 11% of the stems to buckle at SB and 30% of stems to buckle at RM. The percentage of buckled stems under wet conditions varied for different varieties. For example, at SB Consort, Hereward, Reaper, Savannah and Shamrock had about 20% stem buckling compared with 5% for the other varieties. Similar trends were observed at RM.

Table 2.2. *Dates and soil conditions of the tests.*

	RM			SB		
	Dry soil	Wet soil	SED (2 df)	Dry soil	Wet soil	SED (2 df)
Date	3-4 July	10-11 July	n.a.	28-30 June	8-10 July	n.a.
Growth stage	GS71	GS75		GS71-73	GS75-77	
Soil moisture content (gg^{-1})	0.15	0.22	0.006 (**)	0.08	0.19	0.033 (P<0.1)
Soil shear strength (kNm^{-2})	95	42	11.5 (*)	78	28	5.9 (*)

* (P<0.05), ** (P<0.01)

A critical exponential curve accounted for between 85% and 97% of the variation between the angle of shoot rotation and the resisting force measured using Methods 1 and 2. An example of the curves fitted for two of the varieties is shown in Fig. 2.2. This illustrates the large variety differences that were measured for the lodging resistance using Method 1.

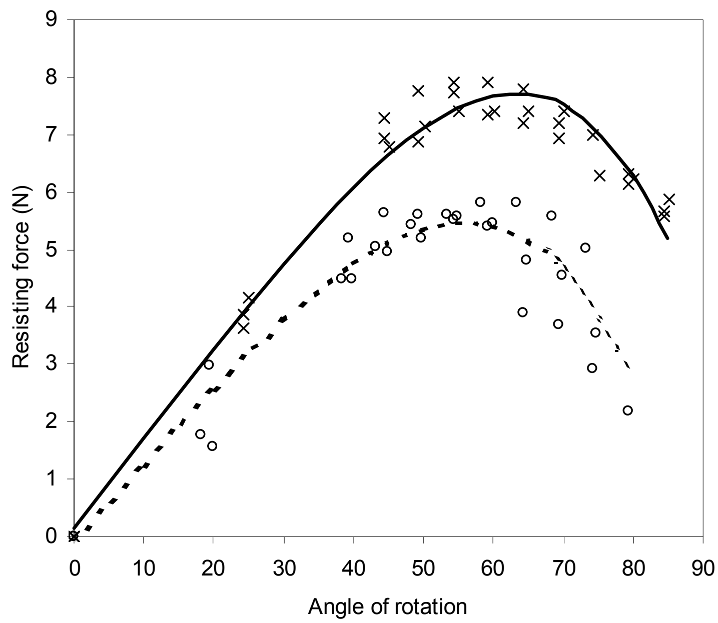

Fig. 2.2. Rotational resistances for a row of shoots in dry soil at SB for Equinox (—) ($y = -14.55 + (14.70 - 0.127x) \times (1.019^x)$; R^2=0.97) and Rialto (---) ($y = -14.87 + (14.65 - 0.137) \times (1.019^x)$; R^2=0.91). Critical exponential curves were fitted to data which was recorded using Method 1.

Table 2.3 shows that Method 1 detected significant variety differences in the force required to cause lodging at both sites and on both wet and dry soil. The lodging resistance varied by up to two fold between varieties. The angle of lodging at which maximum lodging resistance was recorded showed little deviation for variety and soil wetness. At RM it averaged 47^o from the vertical and at SB it averaged 59^o. Encouragingly, the lodging resistances measured under dry conditions at RM and wet conditions at SB predicted the observations of stem and root lodging at the respective sites fairly well. Negative linear relationships accounted for 59% of stem lodging and 50% of root lodging (Figs 2.3a and b). The predictive power of the lodging resistance measured on wet soil at SB was reduced by Consort, Hereward, Shamrock and Equinox, which had low lodging resistances of between 4 and 5N, but experienced small amounts of lodging. It seems likely that, for Consort, Hereward and Shamrock, this was caused by greater amounts of stem lodging compared with the other varieties. The low lodging resistance of Equinox is difficult to explain however. Observations that a greater proportion of the shoots lodged as a result of anchorage failure when the tests were conducted on wet soil compared with dry soil were supported by the significant reduction in lodging resistance on wet soil. At RM, wet soil caused the lodging resistance to decrease by 26%, on average, and a 13% reduction was observed at SB (P<0.001). No significant interaction was detected between variety and soil wetness when the two sites were analysed separately or together. This meant that no differences could be identified for the risks to stem and root lodging for any particular variety using this method.

Table 2.3. *Results of Method 1. Maximum resistance of a row of shoots after force is applied at half of the crop height (N)*

	RM		SB	
	Dry soil	Wet soil	Dry soil	Wet soil
Variety				
Buster	6.80	4.45	7.86	7.45
Cadenza	3.42	2.09	4.73	4.63
Charger	3.90	3.76	3.71	3.41
Consort	5.25	4.54	4.04	3.94
Equinox	7.24	4.94	7.59	5.07
Hereward	5.16	3.02	4.38	5.20
Hussar	4.62	3.66	4.89	4.36
Madrigal	7.70	5.12	6.29	6.53
Mercia	4.33	3.73	6.16	5.44
Reaper	4.24	3.89	5.19	3.13
Rialto	3.85	2.93	5.62	3.98
Savannah	3.35	2.71	7.12	4.56
Shamrock	5.11	3.60	4.92	5.23
Spark	6.17	3.97	8.52	7.09
Mean	5.08	3.74	5.79	5.00
Variety SED (26 df)	1.053 (**)	0.660 (*)	1.028 (***)	0.708 (***)
Soil moisture SED (27 df)	0.716 (***)		0.202 (***)	
Interaction SED (27 df)	0.933 (NS)		0.883 (NS)	

* (P<0.05), ** (P<0.01), *** (P<0.001)

The results of Method 2 (Table 2.4) show that stem or anchorage failure moment varied by at least two fold between varieties. Table 2.5 shows that there was large variation between varieties for the main determinants of base bending moment. For example, at SB, natural frequency varied from 0.64 to 0.96 Hz, height at centre of gravity varied from 484 to 621 mm and ear area varied from 9.6 to 13.5 cm^2. This variation meant that at SB the base bending moment of a shoot experiencing 10 ms^{-1} wind could vary from 0.084 Nm for Shamrock to 0.148 Nm for Rialto. When the stem and anchorage failure moments were combined with the determinants of base bending moment using equations 2.3 and 2.4 the resulting failure wind speeds differed significantly between the varieties (Table 2.4). The failure wind speeds of the most lodging resistant varieties tended to be 3 to 4 ms^{-1} greater than the most lodging prone varieties. The failure wind speeds accounted for slightly more of the variation in observed lodging than the results from Method 1. (Figs 2.3c and d). This improved the R^2 values to 0.63 for stem lodging and 0.53 for root lodging. As with Method 1, Method 2 could not detect a significant interaction between culivar and soil wetness when the two sites were analysed separately or together.

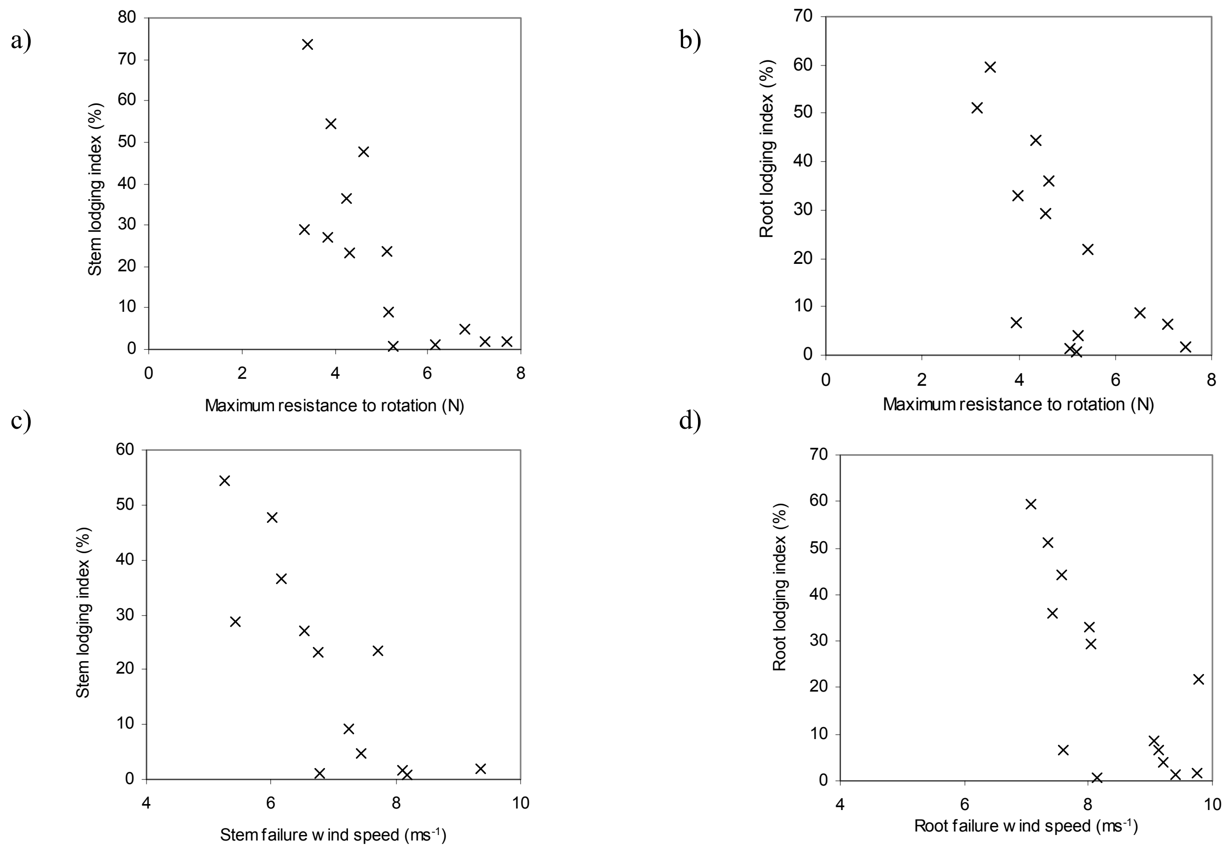

Fig. 2.3 a) Maximum rotational resistance for a row of shoots in dry soil plotted against stem lodging index at RM (y= -12.4x + 87; R^2=0.59).
b) Maximum rotational resistance for a row of shoots in wet soil plotted against root lodging index at SB (y= -11.1x + 77; R^2=0.50).
c) Failure wind speed for shoots in dry soil plotted against stem lodging index at RM (y= -12.5x + 108; R^2=0.63).
d) Failure wind speed for shoots in wet soil plotted against root lodging index at SB (y= -15.6x + 153; R^2=0.53).

Table 2.4. *Results of Method 2*

	RM Stem or Anchorage failure moment per shoot (Nm)		RM Failure wind speed (ms^{-1})		SB Stem or Anchorage failure moment per shoot		SB Failure wind speed (ms^{-1})	
	Dry soil	Wet soil	Dry soil	Wet soil	Dry soil	Wet soil	Dry soil	Wet soil
Variety								
Buster	0.066	0.070	7.45	7.64	0.079	0.080	9.45	9.76
Cadenza	*	*	*	*	0.082	0.076	7.86	7.42
Charger	0.035	0.037	5.25	5.17	0.056	0.054	6.39	7.08
Consort	0.067	0.060	8.19	7.76	0.056	0.072	7.45	7.59
Equinox	0.067	0.075	8.10	8.63	0.076	0.089	8.89	9.41
Hereward	0.056	0.052	7.25	6.98	0.064	0.063	8.25	8.15
Hussar	0.044	0.049	6.02	6.31	0.058	0.071	7.13	7.58
Madrigal	0.088	0.057	9.36	7.68	0.075	0.084	8.56	9.05
Mercia	0.037	0.040	6.75	7.10	0.066	0.091	8.32	9.77
Reaper	0.053	0.039	6.17	6.06	0.042	0.067	6.34	7.35
Rialto	0.049	0.059	6.53	7.74	0.083	0.096	7.08	8.02
Savannah	0.047	0.057	5.42	6.08	0.063	0.087	6.89	8.05
Shamrock	0.056	0.050	7.72	7.37	0.054	0.073	8.03	9.21
Spark	0.052	0.043	6.77	6.12	0.068	0.090	8.03	9.12
Mean	0.055	0.053	7.00	6.97	0.066	0.078	7.76	8.40
Variety SED (26 df)	0.0098 (**)	0.0073 (***)	0.760 (***)	0.771 (**)	0.0097 (*)	0.1265 (NS)	0.622 (***)	0.814 (*)
Soil moisture SED (27 df)	0.0028 (NS)		0.180 (NS)		0.0037 (**)		0.183 (**)	
Interaction SED (27 df)	0.0097 (NS)		0.810 (NS)		0.0137 (NS)		0.780 (NS)	

* (P<0.05), ** (P<0.01), *** (P<0.001)

Table 2.5. *Plant characters which determine the base bending moment of a shoot.*

Variety	RM Natural frequency (Hz)	SB Natural frequency (Hz)	RM Height at Centre of Gravity (mm)	SB Height at Centre of Gravity (mm)	RM Ear area (cm^2)	SB Ear area (cm^2)	RM Shoot base bending moment in 10 ms^{-1} wind (Nm)	SB Shoot base bending moment in 10 ms^{-1} wind (Nm)
Buster	0.63	0.90	537	510	10.24	10.66	0.124	0.089
Cadenza	*	0.64	*	621	*	10.51	*	0.132
Charger	0.62	0.68	514	543	10.04	11.91	0.119	0.133
Consort	0.69	0.79	499	493	9.62	11.37	0.100	0.105
Equinox	0.83	0.96	477	487	11.90	12.35	0.101	0.095
Hereward	0.70	0.88	529	519	10.11	10.81	0.107	0.093
Hussar	0.61	0.71	519	522	10.08	11.05	0.122	0.114
Madrigal	0.65	0.84	464	484	8.59	12.04	0.098	0.104
Mercia	0.73	0.77	492	548	8.32	9.61	0.084	0.094
Reaper	0.59	0.70	522	550	10.99	11.55	0.140	0.125
Rialto	0.72	0.69	503	583	11.32	12.93	0.117	0.148
Savannah	0.57	0.74	521	511	11.80	13.49	0.158	0.133
Shamrock	0.66	0.91	494	508	8.46	10.19	0.092	0.084
Spark	0.61	0.72	553	584	9.09	9.89	0.115	0.107
Mean	0.65	0.78	515	531	9.89	11.26	0.114	0.111
SED (26 df)	0.0601 (*)	0.0388 (***)	12.6 (***)	14.6 (***)	0.601 (***)	0.865 (**)	0.0145 (**)	0.0120 (***)

* (P<0.05), ** (P<0.01), *** (P<0.001)

DISCUSSION

In terms of predicting observations of lodging the results are encouraging. The methods described should correctly identify varieties with high, medium and low lodging resistance in the majority of cases. This level of performance is at least on a par with the methods developed to measure lodging resistance in maize (Fouere *et al.* 1995; Beck *et al.* 1987) and rice (Terashima *et al.* 1992). The two approaches adopted in this paper are also the only ones to be tested against observations of lodging rather than classifications of lodging resistance. Attempts to account for the dynamic nature by which wind loads the shoots, i.e. by including the effect of ear area and natural frequency improved precision by only 6%. This may mean that differences in height (accounted for in Method 1) account for the majority of the differences in base bending moment. Method 1 therefore appears the most useful for providing reasonably reliable data in a short time. This method took about six minutes to perform on each plot. Measurements were taken at ten displacement angles, but it seems likely that the maximum resistance to lodging could be ascertained from fewer measurements concentrated around the failure angles of 40^{o} to 70^{o}, thus reducing the duration of the test. It can also been shown that similar results are achievable by selecting the maximum resistance that was recorded compared with fitting curves to the data and using differentiation to calculate the maximum resistance. This will simplify the data manipulation significantly. After further testing, this method should be useful for identifying lodging prone lines early on in breeding programmes and for classifying varieties for lodging resistance during their testing phase.

The main short-coming of the methods tested was that they did not identify separate rankings for stem and root lodging. Berry *et al.* (2002) investigated the same set of varieties and showed that there are significant differences between the rankings for stem and root lodging risk. The most likely reason for this was a proportion of the stems buckling during the tests on wet soil. This test was designed to measure root lodging resistance, so any stem failure would reduce the accuracy of the estimates of root lodging resistance. This was most apparent at RM where about 30% of the stems buckled during tests in wet soils. This was caused by two factors. Firstly, the soil was only wetted to about 80% of field capacity which meant that it was not at its minimum shear strength. Secondly, a large supply of soil residual nitrogen caused weak stem bases to develop. Together these factors meant that the anchorage failure moment was often greater than the stem failure moment. Root lodging may be promoted at the expense of stem lodging by reducing and delaying nitrogen fertilizer (Berry *et al.* 2000). Carrying out the tests soon after anthesis will also improve the likelihood of root lodging because stem strength declines from this growth stage onwards (Berry 1998). The uneven establishment at SB may also have reduced the chances of detecting differences between the stem and root lodging risks. To confirm that the lodging instrument can detect differences between the stem and root lodging risk further tests should be carried out on several sites and seasons in conditions that allow 0% stem buckling during the root lodging tests.

In general methods to measure the lodging resistance of cereal crops using specially developed instruments have shown, at best, only moderate success. This is probably because in all cases a fundamentally static test is used to replicate a dynamic process. Baker (1995) illustrated that if the wind induced base bending is applied at a plant's natural frequency, the effect can be an order of magnitude larger than if applied at significantly lower frequencies, i.e. those akin to a static test. The published methods are also completed within a matter of minutes. Again this does not replicate natural lodging, which is likely to occur over a longer period (Easson *et al.* 1992) and involve an element of fatigue failure resulting from repeated loading of the base of the plant (Sterling *et al.* 2003). This will probably be sufficient to group varieties into different lodging risk classifications, but for greater precision it seems likely that a test must be developed that causes lodging through repeated loading. The obvious time implications for this type of test would have to be overcome through automation.

REFERENCES

ANON. (2000). *Fertiliser Recommendations for Agricultural and Horticultural crops*. (Seventh Edition). MAFF (now DEFRA) Reference Book 209. London: HMSO.

ANON. (1994). *Cereal Variety Handbook*. Cambridge: National Institute of Agricultural Botany.

ANON. (1999). *Cereal variety handbook*. Cambridge: National Institute of Agricultural Botany.

BAKER, C. J. (1995). The development of a theoretical model for the windthrow of plants. *Journal of Theoretical Biology* **175**, 355-372.

BAKER, C. J., BERRY, P. M., SPINK, J. H., SYLVESTER-BRADLEY, R., GRIFFIN, J. M., SCOTT, R. K. & CLARE, R. (1998). A method for the assessment of the risk of wheat lodging. *Journal of Theoretical Biology* **194**, 587-603.

BECK, D. L., DARRAH, L. L. & ZUBER, M. S. (1987). An improved technique for measuring resistance to root pulling in maize. *Crop Science* **27**, 356-358.

BERRY, P. M. (1998). Predicting lodging in winter wheat. Ph.D. Thesis, Nottingham University, UK.

BERRY, P. M., SPINK, J. H, GRIFFIN, J. M., SYLVESTER-BRADLEY, R., SCOTT, R. K., BAKER, C. J., CLARE, R. W. (1998). Research to understand, predict and control factors affecting lodging in wheat. Home-Grown Cereals Authority Research Project No. **169**. Published by the HGCA, London.

BERRY, P. M., GRIFFIN, J. M., SYLVESTER-BRADLEY, R., SCOTT, R. K., SPINK, J. H, BAKER, C. J., CLARE, R. W. (2000). Controlling plant form through husbandry to minimise lodging in wheat. *Field Crops Research* **67**, 59-81.

BERRY, P. M., SPINK, J. H., SYLVESTER-BRADLEY, R., PICKETT, A. STERLING, M., BAKER, C. J. & CAMERON, N. (2002). Lodging control through variety choice and management. Proceedings of the 8th Home-Grown Cereals Association R&D Conference on Cereals and Oilseeds. HGCA, London, pp 7.1-7.12.

BERRY, P. M., STERLING, M., BAKER C. J., SPINK J. H. & SPARKES, D. L. (2003). A calibrated model of wheat lodging. *Agriculture and Forest Meteorology*. In press.

CROOK, M. J. & ENNOS, A. R. (1993). The mechanics of root lodging in winter wheat, (*Triticum Aestivum* L). *Journal of Experimental Botany,* **44,** 1219- 1224.

CROOK, M. J. & ENNOS, A. R. (1994). Stem and root characteristics associated with lodging resistance in four winter wheat varieties. *Journal of Agricultural Science, Cambridge* **123,** 167-174.

CROOK, M. J. & ENNOS, A. R. (2000). A field based method of quantifying the lodging resistance of wheat varieties. 315-320. Plant Biomechanics Conference Proceedings. Georg Thieme, Stuttgart.

EASSON, D. L., WHITE, E. M. & PICKLES, S. J. (1993). The effects of weather, seed rate and variety on lodging and yield in winter wheat. *Journal of Agricultural Science, Cambridge* **121**, 145-156.

FOUERE, A., PELLERIN, S. & DUPARQUE, A. (1995). A portable electronic device for evaluating root lodging resistance in maize. *Agronomy Journal* **87**, 1020-1024.

GENT, M. P. N. & KIYOMOTO, R. K. (1998). Physiological and agronomic consequences of *Rht* gene in wheat. *Journal of Crop Production* **1**, 27-46.

GRIFFIN, J. M. (1998). Understanding and assessing lodging risk in winter wheat. Ph.D. Thesis, The University of Nottingham, UK.

LANE, P. W. & PAYNE, R. W. (1996). Genstat for windows: an introductory course. Numerical Algorithms Group Limited, Oxford, UK, 154 pp.

NEENAN, M. and SPENCER-SMITH, J.L. (1975) An analysis of the problem of lodging with particular reference to wheat and barley. *Journal of Agricultural Science Cambridge*, **85**, 494-507.

REES, A. L. (1990). The Mechanics of Solids and Structures, McGraw-Hill, London, UK.

STERLING, M., BAKER, C. J., BERRY, P. M. & WADE, A. (2003). Wind induced forces on wheat crops. *Agriculture and Forest Meteorology*. In press.

TERASHIMA, K., AKITA, S. & SAKAI, N. (1992). Ecophysiological characteristics related with lodging tolerance of rice in direct sowing cultivation. 1. comparison of the root lodging tolerance among varieties by the measurement of pushing resistance. *Japanese Journal of Crop Science* **61**, 380-387.

TOTTMAN D. R. (1987). Decimal code for the growth stages of cereals. *Annals of Applied Botany* **110**, 683-687