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### Project identification

1. **Defra Project code**
   - PS2146

2. **Project title**
   - Develop a model of lodging risk in oilseed rape to enable integrated lodging control to reduce PGR use

3. **Contractor organisation(s)**
   - ADAS UK Ltd
   - University of Birmingham (sub contractor)

4. **Total Defra project costs**
   - £ 25,314 (agreed fixed price)

5. **Project:**
   - start date: 01/01/2013
   - end date: 30/09/2013
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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

Develop a model of lodging risk in oilseed rape to enable integrated lodging control to reduce PGR use

PM Berry, C White, M Sterling & C Baker

Lodging is a persistent problem in UK oilseed rape which has been shown to reduce crop yield by 20 to 50% and has been identified as one of the factors responsible for the limited improvement in farm yields. It is estimated that about half of the UK oilseed rape area receives plant growth regulators (PGRs) to reduce the risk of lodging. Several environmental and agronomic factors affect lodging risk in oilseed rape including; wind, rain, soil strength, variety, plant population density, nitrogen nutrition, PGRs and stem diseases. However there is a poor understanding about the degree to which these factors affect lodging. A method of quantifying how variation in each of the above factors and variation in plant characteristics affect lodging risk would allow lodging risk to be minimised. Enabling farmers and crop advisors to develop crop management strategies that maximise lodging resistance, target PGR use at high lodging risk crops and enabling plant breeders to focus on the plant traits that have the greatest impact on lodging risk. The specific objectives of this project included;

1) Develop a theoretical model of the lodging process in oilseed rape
2) Use the model to carry out a sensitivity analysis to identify the most important crop traits and environmental factors that affect lodging
3) Assess how climate change will affect lodging risk
4) Draft a paper describing the lodging model for a peer reviewed journal
5) Detail the further work required to test and further develop the model, and to produce guidelines for avoiding lodging in oilseed rape

This project has developed a theoretical model for estimating the stem and root lodging risk of oilseed rape both for a non interlocking canopy (before pod formation) and for an interlocking canopy (post pod formation). A consideration of the dynamics of the problem showed that, at least in terms of the equations for the wind induced bending moment at the base of the stem, there was a formal mathematical equivalence for the non interlocking and interlocked canopies. This equivalence allows for a considerable simplification in the modelling process, although the input force parameters need to be specified in different ways in each case. It is therefore concluded that, although oilseed rape presents a more complex problem for modelling lodging than cereals, it should be possible to develop a reliable lodging model which
can be used to improve understanding of lodging and reduce its incidence. Several areas require further research in order to develop a reliable lodging model including the nature of the wind above oilseed rape crops, how oilseed rape plants interact with wind especially the drag coefficient for interlocking canopies, root anchorage, stem strength along the length of the stem and inter-dependencies between plant parameters.

The theoretical lodging model shows that typical oilseed rape crops are at risk to both stem and root lodging which indicates that the farming industry must pay equal attention to reducing both stem and root lodging risk. A sensitivity analysis showed that increasing either wind speed or daily rainfall substantially increased lodging risk. The plant parameters which increased lodging risk most included; greater crop height, larger frontal area of the plant, shorter tap root and weaker stem strength. Interestingly all of these plant parameters influenced lodging risk by a similar amount indicating that plant height is not of overriding importance as often perceived. It should be emphasised that the lodging model must be further developed before firm conclusions can be made.

Effects of climate change on oilseed rape lodging risk are difficult to predict due to the high level of uncertainty of how climate change will affect wind speed. If wind speeds remain the same, then the trend towards dryer summers will reduce the risk of root lodging, however the effect is estimated to be small.

Following further lodging model development it will be necessary to test the model in commercial oilseed rape crops. Once the model has been satisfactorily tested it can then be used, in conjunction with field experiments with various crop management treatments, to develop guidelines for crop advisors and farmers to minimise lodging risk.

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**Project Report to Defra**

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:

- the objectives as set out in the contract;
- the extent to which the objectives set out in the contract have been met;
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- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Exchange).
1. Introduction

Lodging is a persistent problem in UK oilseed rape which has been identified as one of the factors responsible for the limited improvement in farm yields (Spink and Berry, 2004). Lodging has been shown to reduce oilseed rape yield by between 20% and 50% (Baylis and Wright, 1990; Armstrong and Nichol, 1991) as well as increasing drying costs. Lodged crops have been estimated to take 5-25% longer to harvest (Baylis and Hutley-Bull (1991). Additionally, the lodging treatments in the trials of Baylis and Wright (1990) had a higher incidence of diseases *Alternaria brassicae* and *Pyrenopeziza brassicae*. Farmers and agronomists ranked lodging resistance as the second most important varietal trait after yield potential in the 2007/8 series of HGCA oilseed rape conferences. Lodging resistance is also one of the highest priority traits for plant breeders.

Lodging compresses the canopy which reduces the transmission of radiation through the pod layer (Berry & Spink, 2006). This is supported by Ward et al., (1985) who observed that more light was able to penetrate the canopy of a standing crop than a lodged one. This reduces overall crop photosynthesis and light use efficiency as the upper pods easily become light saturated due to their limited photosynthetic capacity while the lower pods and leaves receive low light levels (Berry & Spink, 2006). This will reduce the amount of assimilate available for seed filling resulting in smaller individual seed weight. Early lodging during flowering or early pod development is expected to reduce the number of seeds set (seeds/m²) as well as individual seed weight (Berry and Spink, 2009). In general earlier lodging results in greater yield losses (Armstrong and Nicol, 1991; Islam, 1988). Artificial lodging treatment at early pod fill reduced oil content from 43% in supported controls to 41.1% and increased glucosinolate levels from 12.8 µmole/g in supported controls to 13.4 µmole/g (Baylis and Wright, 1990). An inverse relationship between yield and pre-harvest seed loss (as measured by volunteer re-growth) was observed by Baylis and Wright (1990) which suggested that pod shatter may have been a contributory cause of yield loss in lodged crops.

In July 2012 an aerial survey of the prevalence of oilseed rape lodging was commissioned by BASF plc and carried out by ADAS UK Ltd (Kendall et al., 2012). The survey covered over 2000 ha of oilseed rape grown in England and revealed that 35% of this oilseed rape area was lodged. The season of 2011-12 was regarded as a severe lodging season across the UK. Based on lodging-induced yield reductions of 20% to 50% it is estimated that lodging would have cost the UK oilseed rape industry £61 million to £152 million in lost revenue due to reduced yield (assuming an oilseed rape price of £400 per tonne). The lodging would have caused additional costs due to greater drying requirements and slower combining.

As a result of the risk of lodging growers use plant growth regulators (PGRs) in the autumn and spring. The PGR active ingredients available are metconazole, tebuconazole and mepiquat chloride (in combination with metconazole). Metconazole and tebuconazole are also fungicides although their use for disease control has diminished due to the availability of chemicals with greater efficacy such as prothioconazole. In 2010 metconazole was applied to 234,000 ha and tebuconazole was applied to 331,000 ha which represents about 90% of the winter oilseed rape area and 45 t of active substance (Pesticide Usage Survey Report 235). The Mepiquat chloride/metconazole mixture was only registered in 2013. It is estimated that at least half of the oilseed rape area receives metconazole or tebuconazole for growth regulation purposes. Continuing availability of metconazole and tebuconazole may be under pressure as a result of changing legislation in Europe (revision of 91/414/EEC), therefore careful stewardship of these products is required. New PGR products are under development and may supplement/replace the current PGR products.

Several environmental and agronomic factors affect lodging risk in oilseed rape including; wind, rain, soil strength, variety, plant population density, nitrogen nutrition, PGRs and stem diseases (e.g. Berry and Spink, 2009a; 2009b; Spink and Berry, 2004). However there is a poor understanding about the degree to which these factors affect lodging and as a result PGRs tend to be applied to the majority of oilseed rape crops as a safeguard against lodging. A method of quantifying how variation in each of the above factors and variation in plant characteristics affect lodging risk would allow PGR use to be targeted more precisely, and ultimately reduced through:

i) Quantifying the combined lodging risk of several factors so farmers can confidently target PGRs to the crops with the greatest lodging risk.

ii) Quantifying the effect of different factors on lodging risk will enable farmers to develop crop management strategies (variety choice, seed rate, nitrogen nutrition) that minimise lodging risk and the requirement for PGRs.

iii) Identifying the most important lodging traits will help plant breeders to improve the lodging resistance of new varieties.

The aim of this project is to develop a theoretical model of the lodging process in oilseed rape that, following field testing and further development, will ultimately reduce PGR use through routes i to iii above. This work will meet the CRD R&D priorities of sustainable use of pesticides by 1) providing evidence that enables more accurate targeting of PGR chemicals and 2) providing evidence that encourages the development of novel alternative technologies, including lodging resistant varieties and crop management strategies, that will reduce reliance on PGRs. Previous work has shown that intelligent choice of variety, N fertiliser and seed rate can minimise the risk of lodging and significantly reduce requirement for PGRs (Berry and Spink, 2009a), so there is scope for
significant progress to be made in reducing PGR use. The work described in this proposal will meet CRDs overarching aim of providing science and evidence for the sustainable use of pesticides and more specifically meets the objectives of the Alternative Plant Protection theme (AU PS21).

Previous work has investigated the anchorage strength of oilseed rape (Goodman et al., 2001), but no previous research has developed an overall model of lodging in oilseed rape. Previous work on other crop species by crop physiologists and wind engineers funded by HGCA and BBSRC developed a model of wheat lodging (Berry et al., 2003) which has since underpinned much of the current understanding of wheat lodging control. For example, it was used to show that two types of lodging (stem and root) are both important. Unexpectedly it identified variation in stem and anchorage strength as very important determinants of lodging resistance and this led to a current LINK project (LK0958) with a major wheat breeder to develop genetic markers for these traits. The wheat lodging model also underpins the most comprehensive guide that growers and agronomists use to minimise lodging risk (HGCA Guide: Avoiding lodging in winter wheat: Practical Guidelines) as well as being used by the agricultural industry to quantify the effect of PGRs on lodging risk.

It is clear that significant differences in the structure of oilseed rape plants compared with wheat plants will necessitate a different approach to modelling the lodging process in oilseed rape. Key differences include a tap root anchorage system (Goodman et al., 2001), solid stem, different plant morphology between flowering and seed filling, interlocking plant canopy, stem bending/buckling at any point along the stem and greater wind loading per plant. All these aspects must be taken into account in order to develop a reliable model of oilseed rape lodging.
2. Objectives

1) Develop a theoretical model of the lodging process in oilseed rape

2) Use the model to carry out a sensitivity analysis to identify the most important crop traits and environmental factors that affect lodging

3) Assess how climate change will affect lodging risk

4) Draft a paper describing the lodging model for an international peer reviewed journal

5) Detail the further work required to test and further develop the model, and to produce guidelines for avoiding lodging in oilseed rape
3. Develop a theoretical model of the lodging process in oilseed rape

3.1 Understanding of the lodging process in oilseed rape

In oilseed rape lodging can occur at any time between the start of flowering (which usually occurs in April) (Figure 1) until harvest (July or August) (Figure 2). Lodging can result from buckling or bending of the stems (Figures 3 and 4) or failure of the anchorage system (Figure 5). Stem failure can occur at any point along the stem. Anchorage failure occurs as a result of the tap root (Figure 6) rotating or bending within the soil. At the start of flowering oilseed rape plants comprise mainly one main stem (raceme) and there is relatively little inter-locking between neighbouring plants. Branches develop during flowering with the first branches developing near the top of the main raceme and subsequent branches forming lower down the stem. Crops with a high density of plants produce few branches per plant (Figure 7), whereas and crops with a low density of plants produce many branches per plant (Figure 8). As the crop develops the neighbouring plants become more and more inter-locked as first the branches develop and then the pods develop.
3.2. Model development

3.2.1. Outline of the model

The calculation broadly follows the earlier method outlined in Baker (1995) and Baker et al. (1998) for wheat lodging. This involves using Newton’s Law for the canopy top, applying a fluctuating wind load, calculating the bending moment at the base of the stem, and, through models for stem strength and anchorage strength, calculating the critical wind speed and rainfall conditions for stem and root lodging. Clearly there is a major difference between the dynamics of a wheat crop or isolated early season rape, and the fully interlocked late season oilseed rape crop. However a consideration of the dynamics of the problem showed that, at least in terms of the equations for the bending moment at the base of the stem, there was a formal mathematical equivalence, although the input force parameters need to be specified in different ways in each case. This equivalence allows for a considerable simplification in the modelling process. There are a number of other differences between the earlier wheat model and the current oilseed rape model which are described in this section.

- The wheat lodging model of Baker et al. (1998) used a step input of wind speed to represent the wind gust. However the current model attempts to model the honami waves as they pass above the canopy.
- The modelling allows explicit equations to be derived for the mean and unsteady wind induced moments along the length of plant stems, rather than just at the base of the stem as was the case in the wheat model.
- The risk of stem lodging is calculated, as in previous models, by comparing the wind induced bending moment with the stem failure moment (stem strength at point of failure).
- The risk of root lodging also follows the same methodology as in the earlier model, by comparing the wind induced bending moment with the anchorage failure moment (anchorage strength at the point of failure). Although the root structure of oilseed rape is very different from that of wheat and a different formulation for anchorage strength has been used.

The model of Baker et al. (1998) used a measured time series of wind and rainfall for a number of years of data, to determine the overall risk of lodging. In the current method we adopt a more rigorous probabilistic methodology as follows.

- For a particular average set of plant conditions, applying to a particular month in the growing season, means and standard deviations of all the parameters used in the model are specified, and 1000 realisations of all the parameters calculated from assumed probability distributions.
- For each set of realisations the mean hourly wind speed at which stem lodging will occur is calculated and the daily rainfall required for root lodging at different hourly mean wind speeds are also calculated. Taken together all the realisations give probability distributions of stem and root lodging for a matrix of wind speed and rainfall values.
- The actual combined probability distributions for mean wind and daily rainfall are then obtained from meteorological data, from a number of years of data for the specific month under consideration.
• The lodging probability distributions are then convoluted with the wind/rain probability distributions to obtain an overall probability of lodging for a specific set of average plant parameters.

• The variation of the risk with changes in plant parameters, or changes in the wind/rain probability distributions to represent climate change effects, can then be investigated.

3.2.2. Basic equations

For an interlocking rape canopy the basic equation of motion is given by

\[ npEI \frac{d^2y}{dx^2} = mg(Y - y') + \left( F + K \frac{dy}{dt} + C \frac{dy}{dt} \right) (X - x) - m \frac{d^2y}{dt^2} (X - x) \]  \hspace{1cm} (1)

\( x \) is distance up the stem from the ground, \( y \) is the displacement of the stem at \( x \), \( z \) is the distance in the \( y \) direction from a fixed point at the edge of the crop, and \( t \) is time. \( Y \) is the displacement of the top of the stem, and \( X \) is the height of the crop. \( n \) is the number of branches per plant and \( p \) is the number of plants per unit area, \( E \) is the Young’s modulus of the stem, \( I \) is the second moment of area of the stem, \( m \) is the mass of the unit area of the canopy, \( F \) is the wind induced force per unit area of crop, \( K \) and \( C \) are the damping coefficients per unit area of crop. The same equation applies for a single plant, but then \( n, F, K \) and \( C \) have to be interpreted as values per plant, rather than per unit area. Physically the term of the left hand side is the overall bending moment in the stems; the first term on the right hand side is the moment in the stem due to the displaced weight of the canopy; the second term on the right hand side is the sum of the aerodynamic force and the damping forces due to the canopy interactions and the stem material properties; and the third term on the right hand side is the canopy acceleration term.

We assume that the forcing wind force is given by

\[ F = Fe^{i(kx + \omega t)} \]  \hspace{1cm} (2)

i.e. a wave function representing the honami above the top of the crop, with a wave number of \( k \) and a frequency of \( \omega \). The wave velocity will be defined in what follows as \( c = (\omega/k) \). The parameters that are of interest in what follows are the moment in the stem \( M \) and the displacement \( Y \) at the top of the crop. The former is given by

\[ M = -EI \frac{d^2y}{dx^2} \]  \hspace{1cm} (3)

After much manipulation, one obtains the expressions

\[ \frac{mgY}{FX} = \left( \frac{1 + 0.5n^2}{(0.5n^2 + (\alpha n)^2)} \right) \]  \hspace{1cm} (4)

\[ \frac{M}{FX} = \left( \frac{1 + 0.5n^2}{(0.5n^2 + (\alpha n)^2)} \right) \cos(\alpha \bar{x}) - \cot \alpha \sin(\alpha \bar{x}) \]  \hspace{1cm} (5)

The symbols are defined as follows

\[ \bar{x} = \frac{x}{\bar{x}} \]  \hspace{1cm} (6)

\[ \alpha = \left( \frac{mg \bar{x}^2}{npE} \right) \]  \hspace{1cm} (7)

\[ \bar{\omega}_n = \omega_n \left( \frac{X}{\bar{X}} \right) = \left( \frac{\tan(\alpha)}{\alpha^2 - \tan(\alpha)} \right)^{0.5} \]  \hspace{1cm} (8)

\[ \bar{\omega} = \omega \left( \frac{X}{\bar{X}} \right)^{0.5} \]  \hspace{1cm} (9)

\[ \omega = \frac{\pi \bar{\omega}}{2\bar{x}} \]  \hspace{1cm} (10)

\[ \theta = \left( \frac{X}{mg} \right) \left( \frac{\bar{X}}{X} \right)^{0.5} \]  \hspace{1cm} (11)

Here \( \bar{x} \) is the dimensionless distance up the stem, \( \bar{\omega}_n \) is the dimensionless natural frequency, \( \bar{\omega} \) is the dimensionless honami frequency and \( \theta \) is the overall damping ratio. Both \( \omega_n \) and \( \theta \) should be able to be obtained experimentally from field tests, without the need to calculate them from their components. The expression for \( \omega \) comes from a consideration of the results of Finnigan (1979), but can only be regarded as an approximation.

Now consider the wind force. This is taken to be given by a mean component and a fluctuating component. The mean component is given by

\[ F = 0.5 \rho A U^2 C_f \]  \hspace{1cm} (12)
where $\rho$ is the density of air, $A$ is either 1.0 for a connected canopy or the effective plant area that intercepts the wind for an isolated plant, $\bar{U}$ is the mean velocity at the top of the canopy and $C_f$ is a force coefficient (either the force per unit area for a connected canopy or the force on the canopy exposed area for an isolated plant). The fluctuating component is given by
\[ F' = \rho A \bar{U}^2 C_f k l \]  (13)
where $l$ is the turbulence intensity and $k$ is a factor that represents the difference between the peak of the homom gust and the mean velocity. For a sinusoidal gust, $k$ should be $\pi^{0.5}$.

### 3.2.3. Bending moment calculation

Although the model can calculate the variation of bending moment up the stem, as there is no information on the variation of stem strength with distance along the stem for rape, we assume that stem lodging will occur at the stem base, and are thus only interested in the bending moment at this point. From the above equations one can derive the following expressions for mean and fluctuating bending moments at the stem base.

\[ M = \frac{1 + \frac{a^2}{2}}{a} (0.5 \rho \bar{U}^2 C_f A X) \]  (14)
\[ M' = \frac{1 + \frac{a^2}{2}}{((a^2 - \alpha^2)^2 + (\alpha \delta)^2)} (\rho k \bar{U}^2 A C_f X) \]  (15)

The total overall moment at the stem base is given by
\[ M = M + M' = \frac{1 + \frac{a^2}{2}}{a} (0.5 \rho \bar{U}^2 C_f A X) \left( 1 + \frac{\frac{\delta^2}{a^2 - \alpha^2} + (\alpha \delta)^2}{(\alpha \delta)^2} k l \right) \]  (16)

### 3.2.4. Stem lodging

If stem lodging occurs, the bending stress due to the imposed wind load will exceed the stem strength at the base of the stem. This gives the following expressions

\[ M > (\sigma a^3/4) \left( 1 - \left( (a - t)/a \right)^4 \right) \] for the non-interlocking canopy (17)
\[ M/np > (\sigma a^3/4) \left( 1 - \left( (a - t)/a \right)^4 \right) \] for the interlocking canopy (18)

where $\sigma$ is the stem yield stress; $a$ is the stem external diameter and $t$ is the stem wall thickness. From these expressions, and the equations for the base bending moment it is possible to find the average wind speed at which stem lodging will occur for a specific set of plant parameters.

### 3.2.5. Root lodging

We assume the following form for the root lodging model (based on the rather inconclusive work of Goodman et al., 2001)
\[ R = \gamma \tau d l^2 \]  (19)
where $R$ is the resisting moment, $s$ is the soil shear strength, $d$ is the tap root diameter and $l$ is the tap root length. $\gamma$is a constant that will be taken as 4.0 (but see below). Failure thus occurs when

\[ s = Mn/\gamma dl^2 \] for the non-interlocking canopy (20)
\[ s = Mpn/\gamma dl^2 \] for the interlocking canopy (21)

The daily mean rainfall for root lodging to occur can then be found from the expressions used in the earlier lodging model for wheat (Baker et al., 1998).

\[ i = \frac{f - w)((\rho_s/\rho_w)(s_D - s))}{s_D - s_w} \] if $s < s_D$  (22)
\[ i = (f - w))\rho_s/\rho_w \] if $s_D < s < s_w$
\[ i = (f - w))\rho_s/\rho_w \] if $s_w < s$

where $w$ is the water content at wilting point; $f$ is the water content at field capacity; $c$ is the clay content; $v$ is the visual score; $\rho_s$ is the density of soil; $\rho_w$ is the density of water; $s_D = s$ for dry soil; $s_w = s$ for saturated soil. The latter two parameters are given by

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\[ s_D = 1125e^{s_D} (2.2 - 0.24v)(4.82c - 0.3) \]  
\[ s_w = 1484e^{s_D} (2.2 - 0.24v)(4.82c - 0.3) \]

### 3.2.6. Lodging probability calculations

To calculate the overall probability of lodging the following procedure is followed.

- The means and standard deviations of the various plant and soil characteristics are suitably defined.
- 1000 realisations of sets of these parameters, that are consistent with the specified means and standard deviations, are then calculated using EXCEL random number generator.
- For each realisation the wind velocity required for stem lodging is calculated, and thus a probability distribution of stem lodging probability as a function of wind speed can be calculated \( F_{SL}(\bar{U}) \).
- For each realisation, the base bending moment is calculated for a range of wind speeds, and the above equations (20) to (24) used to calculate the daily mean rainfall that would result in root lodging for each wind speed in each realisation, and thus the combined cumulative probability distribution function for root lodging as functions of average wind speed and mean daily rainfall can be calculated \( F_{RL}(\bar{U}, i) \).
- The combined total lodging cumulative probability can then be calculated from
\[ F_{TL}(\bar{U}, i) = F_{SL}(\bar{U}) + (1 - F_{SL}(\bar{U}))F_{RL}(\bar{U}, i) \]  
- The cumulative mean wind / daily rainfall probability distribution function \( F_{met}(\bar{U}, i) \) can then be determined from long meteorological data time series.
- The overall risk of lodging is then calculated from the convolution of \( C_{TL}(\bar{U}, i) \) and \( F_{met}(\bar{U}, i) \)

### 3.2.7. Issues

It is clear that the above methodology will require detailed information concerning the geometric and mechanical properties of rape. Much of this data is not yet available, although it could be obtained fairly straightforwardly from comprehensive field experiments. However there are a number of other modelling issues that need to be tested against field data.

- The nature of the honami gusts above rape crops and in particular their scale and frequency.
- The variation of the values of crop natural frequency, damping ratio and drag coefficient throughout the growing season needs to be determined. Data on the drag coefficient for an inter-locking canopy will be particularly important.
- The nature of the root strength model – field data for a range of conditions is required to confirm this.

### 3.3. Review of oilseed rape crop parameters associated with lodging resistance

#### 3.3.1. Tap root

The standard UK crop parameters associated with lodging resistance, together with the range of values, are shown in Table 1. The tap root measurements in commercial reports for BASF produced by ADAS UK Ltd were assessed at four to six weeks after the sixth leaf stage (GS1,6) (using the growth stage key of Sylvester-Bradley & Makepeace, 1984). The average tap root length was 126 mm, (range 94 to 142 mm). The length of the tap root was taken to be the distance from the base of the shoot where the leaves emerge to where the tap root was less than 1 mm wide. The tap roots were tapered (becoming thinner with greater soil depth). The average tap root width at the top of the tap root was 6.4 mm (range 3.7 to 8.2 mm) and was measured just below where the leaves emerge. Goodman et al., (2001) assessed crop parameters when the pods had developed and the seeds were green (GS6,3). The length of the rigid tap root was taken to be the length from the stem base to the point at which the root no longer resisted bending. The average rigid tap root length was 123 mm (range 117 to 129 mm) which is similar to the average tap root length as assessed at early growth stages in the BASF commercial reports. The tap root diameter was measured at the top of the tap root, and the average was 16.5 mm (range 11 to 20 mm), which was greater than the mean tap root width assessed in the BASF commercial reports.

#### 3.3.2. Stem properties

The stem diameter and stem failure moment were measured at the base of the stem in Goodman et al. (2001) after flowering and in a BASF commercial report produced by ADAS UK Ltd on the bottom 0 – 30 cm section of the stem at the end of flowering. The mean stem diameter was 11 mm (range 7 to 17 mm) and the mean stem
failure moment was 3.3 Nm (range 2.4 to 4.3 Nm). The stem wall width was only assessed in one BASF commercial report and was 2.21 mm (range 0.85 – 2.21 mm).

3.3.3. Canopy properties
The average final crop height measured in several HGCA Recommended List variety trials (www.hgca.com) was 152 cm (range 99 to 178 cm). Final height is normally reached at the end of flowering. Total fresh weight per plant at mid-flowering was an average of 79.8 g (range 64 to 96 g) and the average total fresh weight per plant pre-harvest was 87.4 g (range 74 to 118 g). The number of primary branches (including the terminal raceme) per plant was assessed at the end of flowering and was an average of 8.2 (range 6.9 to 9.1). The average green area at mid-flowering was 2.03 m² (range 0.32 to 4.8 m²) and the average green area per plant was 0.027 m² (range 0.021 to 0.043 m²). Four weeks after the end of flowering the average projected (one side only) pod green area was 2.54 m² (range 0.9 m² to 6.11 m²) and the average projected pod green area per plant was 0.027 m² (range 0.021 to 0.043 m²). The number of pods per plant averaged 96 with a range of 43 to 142. The average projected area of an individual pod was 3.9 cm² (range 1 to 6.26 cm²). The average projected area of an individual pod at harvest was 4.8 cm² (range 2.88 to 7.96 cm²).

Table 1. Mean UK oilseed rape crop parameters associated with lodging together with the range of values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Range</th>
<th>Standard deviation</th>
<th>Reference</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tapp root length (mm)</td>
<td>126</td>
<td>94 – 142</td>
<td>21.8</td>
<td>GS1,6 + 5 weeks n=5</td>
<td></td>
</tr>
<tr>
<td>Tapp root length (mm)</td>
<td>123</td>
<td>117 – 129</td>
<td>1</td>
<td>GS6,3 n=15</td>
<td></td>
</tr>
<tr>
<td>Tapp root width (mm)</td>
<td>6.40</td>
<td>3.72 – 8.17</td>
<td>1.96</td>
<td>GS1,6 + 5 weeks n=5</td>
<td></td>
</tr>
<tr>
<td>Tapp root width (mm)</td>
<td>16.5</td>
<td>3.72 – 18.7</td>
<td>1</td>
<td>GS6,3 n=15</td>
<td></td>
</tr>
<tr>
<td>Crop height (cm)</td>
<td>152</td>
<td>99 – 178</td>
<td>13.8</td>
<td>2, 3, 4 n=51</td>
<td></td>
</tr>
<tr>
<td>Primary branch number/plant</td>
<td>8.2</td>
<td>6.9 – 9.1</td>
<td>0.91</td>
<td>2 n=8</td>
<td></td>
</tr>
<tr>
<td>Mid-flowering total fresh weight per plant</td>
<td>79.8</td>
<td>64.0 – 96.0</td>
<td>12.0</td>
<td>5 n=8</td>
<td></td>
</tr>
<tr>
<td>Pre-harvest total fresh weight per plant</td>
<td>87.4</td>
<td>74.0 – 118.0</td>
<td>14.9</td>
<td>5 n=8</td>
<td></td>
</tr>
<tr>
<td>Stem diameter (mm)</td>
<td>11.1</td>
<td>7.31 – 17</td>
<td>1, 2</td>
<td>n=2</td>
<td></td>
</tr>
<tr>
<td>Stem wall width (mm)</td>
<td>2.21</td>
<td>0.85 – 3.57</td>
<td>2</td>
<td>n=10</td>
<td></td>
</tr>
<tr>
<td>Stem failure moment (Nm)</td>
<td>3.32</td>
<td>2.40 – 4.25</td>
<td>1, 2</td>
<td>n=10</td>
<td></td>
</tr>
<tr>
<td>Pod green area at mid-seed fill (m² per m² ground)</td>
<td>2.03</td>
<td>0.32 – 4.80</td>
<td>1.53</td>
<td>5 n=46</td>
<td></td>
</tr>
<tr>
<td>Pod area at harvest (m² per m² ground)</td>
<td>2.54</td>
<td>0.9 – 6.11</td>
<td>1.20</td>
<td>5 n=46</td>
<td></td>
</tr>
<tr>
<td>Pod green area per plant at mid-seed fill (m²)</td>
<td>0.041</td>
<td>0.006 – 0.096</td>
<td>0.03</td>
<td>4, 5</td>
<td></td>
</tr>
<tr>
<td>Green area per pod at mid-seed fill (cm²)</td>
<td>3.86</td>
<td>1.00 – 6.26</td>
<td>4, 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area per pod at harvest (cm²)</td>
<td>4.82</td>
<td>2.88 – 7.96</td>
<td>4, 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pod number per plant</td>
<td>95.5</td>
<td>43.2 – 142.2</td>
<td>28.9</td>
<td>4, 5, 6 n=10</td>
<td></td>
</tr>
</tbody>
</table>

Key to references: 1, Goodman et al. (2001); 2, Commercial BASF reports; 3, HGCA Recommended list guide 2013/14; 4, HGCA project report no. OS64; 5, HGCA project report no. OS49; 6, AHDB Project report no. 495. n – number of experiments.
4. Lodging model output and sensitivity analysis

The prototype model of oilseed rape lodging estimates the probability of stem lodging and root lodging based on information provided about the wind characteristics of the site, rainfall, soil type, and crop characteristics. In this analysis the bending moment formulae for a non-interlocking canopy has been used and the frontal area per branch and branch number per plant have been combined into the single parameter of frontal area per plant. Lack of data describing the wind force drag characteristics over an inter-locking canopy means that a sensitivity analysis for this type of crop would be uncertain. Table 2 summarises estimated standard UK values and ranges for each of the model parameters. Where possible the standard and range values are based on observations described in Table 1. However, it should be recognised that some of the estimations are based on only a few observations and some estimations are simply author estimates such as for natural frequency, damping ratio and drag coefficient.

Table 2. Ranges of the standard parameters expected in the UK.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard value</th>
<th>Range of values for UK</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Meteorological and site parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean wind speed 10m above ground (m/s)</td>
<td>2</td>
<td>1 to 6</td>
</tr>
<tr>
<td>Turbulence intensity</td>
<td>0.2</td>
<td>0.1 to 0.3</td>
</tr>
<tr>
<td>Daily rainfall (mm)</td>
<td>2</td>
<td>0 to 16</td>
</tr>
<tr>
<td><strong>Soil parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay content (g/g)</td>
<td>0.25</td>
<td>0.2 to 0.4</td>
</tr>
<tr>
<td>Visual score</td>
<td>5</td>
<td>2 to 8</td>
</tr>
<tr>
<td>Water content at permanent wilting point (g/g)</td>
<td>0.15</td>
<td>0.10 to 0.20</td>
</tr>
<tr>
<td>Water content at field capacity (g/g)</td>
<td>0.27</td>
<td>0.20 to 0.35</td>
</tr>
<tr>
<td><strong>Crop parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plant height (m)</td>
<td>1.5</td>
<td>0.8 to 2.0</td>
</tr>
<tr>
<td>Frontal area per plant (m²)</td>
<td>0.04</td>
<td>0.01 to 0.10</td>
</tr>
<tr>
<td>Natural frequency (Hz)</td>
<td>0.5</td>
<td>0.25 to 1.0</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>1.0</td>
<td>0.5 to 1.5</td>
</tr>
<tr>
<td>Damping ratio</td>
<td>1.0</td>
<td>0.7 to 1.3</td>
</tr>
<tr>
<td>Stem failure moment (Nm)</td>
<td>3.0</td>
<td>1.5 to 4.5</td>
</tr>
<tr>
<td>Stem base diameter (mm)</td>
<td>11</td>
<td>7 to 17</td>
</tr>
<tr>
<td>Stem wall thickness (mm)</td>
<td>2.2</td>
<td>0.8 to 3.6</td>
</tr>
<tr>
<td>Stem material strength (MPa)</td>
<td>5</td>
<td>3 to 7</td>
</tr>
<tr>
<td>Tap root thickness (mm)</td>
<td>12</td>
<td>5 to 20</td>
</tr>
<tr>
<td>Tap root length (mm)</td>
<td>150</td>
<td>50 to 250</td>
</tr>
</tbody>
</table>

The lodging model has been run for a range of wind speeds and rainfall amounts, with the standard values described in Table 2 used for all other model parameters. This showed that the probability of stem lodging increased from zero for a mean daily wind speed of less than 1 m/s, rising to a lodging probability of 0.9 for a mean daily wind speed of 5 m/s (Figure 9). In the absence of rainfall the probability of root lodging reached a maximum of 0.44 at a wind speed of 5 m/s. The probability of root lodging increases substantially when the daily rainfall is increased to 12 mm because rain increases the water content of the soil which reduces its shear strength.
A sensitivity analysis has been carried out by varying each model parameter about its minimum and maximum range (as described in Table 2) and keeping all other model parameters at their standard values. Changes in wind speed have a large effect on the probability of root and stem lodging (Figures 10 and 11). Increasing the daily rainfall above 2 mm causes a rapid rise in the risk of root lodging (Figure 10). Changes in turbulence intensity have relatively modest effects on the risk of lodging.

Of the soil parameters, the clay content had the greatest effect on the probability of root lodging with higher clay content resulting in a stronger soil and anchorage (Figure 12). The effect of the soil water content at permanent wilting point had a modest effect on root lodging risk. Varying the visual score of the soil (which is a measure of its crumb structure, with a high score indicating a well structured soil) and soil water content at field capacity had a small effect on root lodging risk. Lengthening the tap root from 50 mm to 250 mm reduced the probability of root lodging from more than 0.8 to less than 0.3 (Figure 13). Increasing the width of the tap root had a modest effect on the probability of root lodging.
Of the crop parameters that affect the bending moment of the crop canopy on the stem base and anchorage system, variation in crop height and the frontal area of the plant had the greatest effect on lodging probability (Figure 14). Variation in drag coefficient had a moderate effect, although little is actually known about the range of this character. Variation in natural frequency and damping ratio had little effect on lodging probability.

Variation in stem failure moment and its components (stem diameter, stem wall width and material strength) all had a substantial effect on stem lodging (Figure 15).

In summary, the sensitivity analysis has shown that, given modest amounts of rainfall of just a few millimetres, typical oilseed rape plants are at risk to both stem and root lodging. The probability of lodging is substantially increased by higher wind speeds, greater rainfall and weaker soil. The key plant parameters that affect the chance of lodging include crop height, the frontal area of the plant, stem strength and the length of the tap root. This sensitivity analysis was carried out using the bending moment formulae appropriate for a non-interlocking canopy and different results may be obtained for an inter-locking canopy. Further research is required to investigate whether all of the plant parameters are independent of each other. For example, widely spaced plants usually have both a larger frontal area, thicker stems and thicker tap roots.
5. Effects of climate change on lodging risk

The fundamental climate parameters used in the lodging model are the joint probability distributions of wind and rainfall. In principle these distributions can be parameterised in a relatively straightforward way. Expressing the meteorological data in this way is convenient for the study of climate change effects, since climate change scenarios are usually based on the changes to the probability distributions of climate parameters. Now whilst the UKCP09 predictions for the variation of rainfall probability distributions are well specified, with the UK showing an overall trend towards wetter winters and drier summers, the same cannot be said concerning wind speed probability distributions. These are far from being well specified, and wind speed predictions are in fact not included in the UKCP09 scenarios. Similarly the weather generator associated with UKCP09 does not model wind well, and attempts to do so, by back calculations from evapo-transpiration, have not been very successful. Recent work underway as part of the research councils ARCC programme, looking at the probabilistic variation of storm tracks across the UK, holds some promise of a resolution of this issue, although there is still much work to be done. Thus as things stand, the best way of dealing with climate change effects on rape lodging would be to assume that the joint wind / rainfall probabilities should be shifted along the rainfall axis to replicate the rainfall probability for the different climate scenarios of UKCP09, with the wind axis being left as it is. This is far from ideal, but this limitation is imposed by the current state of the art in climate predictions.

The UKCP09 middle high scenario for the UK midlands in 2080 is for a 20% reduction in summer rainfall. If the oilseed rape lodging model is adjusted for 20% less rainfall, whilst keeping the wind speed probabilities unaltered, then the combined stem and root lodging probabilities for a range of crops decreases by 6% on average (Figure 16). The reduction in rainfall reduces the chance of root lodging by reducing the likelihood that the soil strength is reduced below the critical value required to anchor the crop. Crops with a range of tap root lengths have been used to evaluate the effect of less rain on lodging risk because this gives crops with a high probability of root lodging (short tap roots) and crops with a low probability of root lodging (long tap roots).

![Figure 16. Effect of a 20% reduction in rainfall on the combined probability of stem and root lodging for crops with a range of tap root lengths. Wind speed probabilities have been kept the same for both rainfall scenarios.](image-url)
6. Further work required

6.1 Model development
Several areas of new information about the mechanical and geometric properties of oilseed rape grown in the field are required in order to develop the lodging model further to a point where it is ready for field testing. Key areas for further model development include:

- The nature of the honami gusts above rape crops and in particular their scale and frequency.
- The variation of the values of crop natural frequency, damping ratio and drag coefficient throughout the growing season needs to be determined. Gathering data on the drag coefficient for an inter-locking canopy will be particularly important.
- The nature of the anchorage strength model – field data for a range of conditions is required to confirm this.
- Quantify the variation in stem strength along the length of the stem to enable the risk of stem failure at different points along the stem to be calculated.
- Investigate the degree of independence between plant traits, e.g. plants with a large frontal area may also have a longer tap root.

The measurements associated with understanding how the crop canopy interacts with wind would need to be done in commercial oilseed rape crops in order to be relevant. The use of high specification sonic anemometers in association with video analysis of the plant's movement would be required to understand how oilseed rape plants interact with wind and to verify the underlying principles of the lodging model. Wind tunnel tests will be required to better specify many of the model parameters. Ideally the model development and model testing (described below) would occur simultaneously which would allow an iterative process of model development – testing – development – testing etc…

6.2 Model testing
The lodging model must be field tested by investigating how well it predicts natural lodging incidences. In order to achieve this it will be necessary to set up field experiments with treatments that give a wide range of lodging risks. This can be done by manipulating variety choice and through the use of seed rate, nitrogen fertiliser and PGRs. The lodging model would be used to estimate the lodging risk of the treatments by inputting measurements of the lodging parameters made on the test crops. The estimates of lodging risk would then be compared with observations of natural lodging. The likelihood of lodging could be maximised by choosing windy sites or/and by irrigating the field experiments.

6.3 Guidelines for minimising lodging risk
Once the model has been proven to be reliable it could be used to quantify the risk of different environmental conditions (e.g. soil conditions) and different crop management including; variety choice, sowing date, seed rate, nitrogen fertiliser rate and timing and PGRs. This information could then be used to develop a quantitative guide that crop advisors and farmers can use to plan crop management strategies (involving variety choice, sowing date and seed rate) and crop management tactics in spring (involving nitrogen fertiliser and PGRs) that minimise the risk of lodging. Several field experiments would need to be set up in order to generate the information required for reliable guidelines. Each field experiment would have a range of crop management treatments.

6.4 Breeding lodging resistant varieties
The lodging model will be used to identify the most important plant traits that plant breeders must focus on in order to increase the lodging resistance of new varieties. It is likely that some of the key plant traits will be time consuming to measure (e.g. tap root dimensions). This is a problem for plant breeders as they must screen large numbers (100s to 1000s) of breeding lines. Therefore research will be required to develop rapid screening methods. These should take the form of new instrumentation which allow rapid measurement in the field and the development of reliable genetic markers that allow breeding lines to be evaluated simply by screening their DNA.
7. Conclusions

- This scoping study has described the framework of a lodging model for oilseed rape using current understanding about how crops interact with the wind and soil.

- The authors conclude that, although oilseed rape presents a more complex problem for modelling lodging than cereals, it should be possible to develop a reliable lodging model which can be used to improve understanding of lodging and reduce its incidence.

- Several areas require further research in order to develop a reliable lodging model including the nature of the wind above oilseed rape crops, how oilseed rape plants interact with wind, root anchorage, how stem strength varies along the length of the stem and inter-dependencies between plant parameters.

- The theoretical lodging model indicates that, given only a modest amount of rainfall, typical oilseed rape crops are at risk to both stem and root lodging. This is an important finding which if substantiated by a validated model would mean that the farming industry must pay equal attention to reducing both stem and root lodging risk.

- The model of oilseed rape developed in this study was used to identify which environmental and plant parameters are likely to influence lodging risk the most. Increasing both wind speed and daily rainfall substantially increased lodging risk. The plant parameters which increased lodging risk most included; greater crop height, larger frontal area of the plant, shorter tap root and weaker stem strength. Interestingly all of these plant parameters influenced lodging risk by a similar amount indicating that plant height is not of overriding importance as often perceived. However, it should be emphasised that the lodging model must be further developed before firm conclusions can be made.

- Effects of climate change on oilseed rape lodging risk are difficult to predict due to the high level of uncertainty of how climate change will affect wind speed. If wind speeds remain the same, then the trend towards dryer summers will reduce the risk of root lodging, however the effect is estimated to be small.

- Following further lodging model development it will be necessary to test the model in commercial oilseed rape crops. Once the model has been satisfactorily tested it can then be used, in conjunction with field experiments with various crop management treatments, to develop guidelines for crop advisors and farmers to minimise lodging risk.

- A reliable lodging model will identify which plant traits plant breeders should focus on to develop new varieties with high lodging resistance.
8. References


