A calibrated oat lodging model compared with agronomic measurements

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Abstract.

For the first time, this research enables a systematic parametric analysis of oat lodging to be undertaken. A generalised lodging model combining agronomy, biology and wind engineering has been used. Standard husbandry treatments have been deployed in order to ensure that the oat plants are grown in realistic conditions and to ensure that the results are widely applicable. It is shown that the drag area, which increases through the growing season as the oats become entangled, is the plant trait which influences both stem and root lodging the most. In addition (and consistent with other plants) stem yield stress and the number of stems per plant for stem lodging and the diameter of the root structure in the case of root lodging, are found to play an important role. It is also shown that there is a linear relationship between failure anchorage moment and the cube of the root diameter in oats. Moreover, monitoring the lodging in crops which were grown under different husbandry treatments revealed using a resistant variety coupled with low Nitrogen rates and low seed rates, whilst also applying a Plant Growth Regulator (PGR) can increase the resistance of oat against lodging.

Keywords
Lodging; Model; Oat; Bending moment; Crop failure

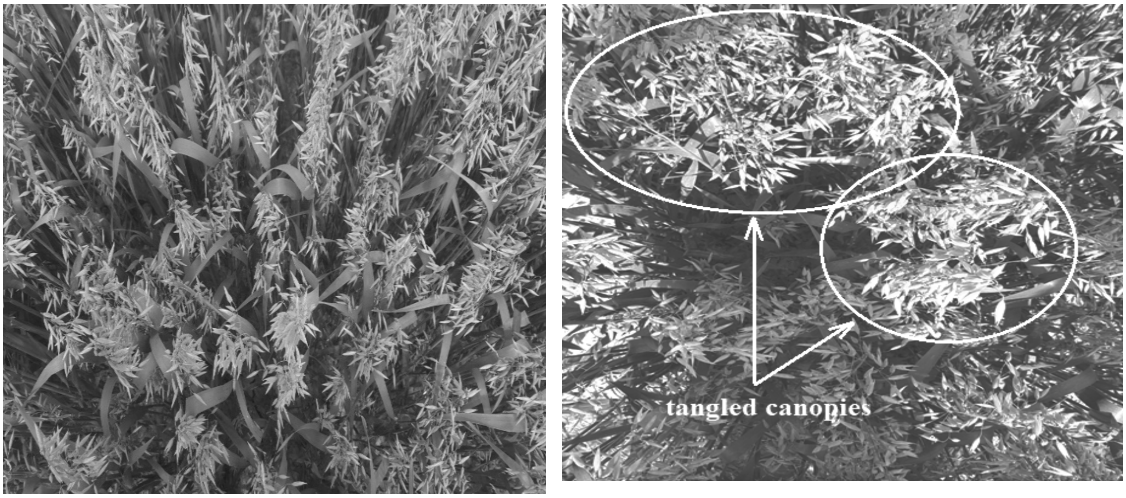
1. Introduction

Lodging, the failure of a crop at the root or the stem due to the action of the wind/rain can be a considerable problem in the agriculture industry resulting in millions of pounds sterling of annual damage worldwide (Baker et al., 2014; Sterling et al., 2018). The problem is more significant in farmlands facing strong winds and wet conditions due to high regional rainfall or need of irrigation (Baker et al., 2014). For example, in the UK severe lodging has been observed every 3-4 years and the annual lodging cost could reach to 170 million pounds sterling in cereals and oilseed rape crops, which is mainly as the result of yield loss. Additionally, the costs incurred by lodging can arise from reduced grain quality, greater drying costs and slower harvest (Berry et al., 2004; Berry et al., 2003; Sterling et al., 2018).

Although primary observations showed that lodging could happen as a failure in the stem or at the roots, plant characters that have greatest influence on lodging for each type of lodging and ways to prevent lodging were the subject of debate for several years (Berry et al., 2000; Berry et al., 2004). Crop management decisions such as seed rate, variety choice, sowing date and Nitrogen application rate are some of the factors frequently referenced in the literature as contributory factors to lodging since they can affect the plant parameters associated with lodging (Berry, 2002; Berry et al., 2004). Rainfall can decrease the soil strength and thereby decrease the anchorage of the plant making it more susceptible to lodging (Baker et al., 1998; Berry et al., 2000). The wind speed governs the forces which have an impact on the plant and thus directly affect its ability to remain vertical (Sterling et al., 2003; Berry et al., 2000). In order to investigate this in a systematic manner, Baker (1995) developed a mechanical model which assumed that the plant could effectively be represented as two masses representing the root/soil structure and the plant's ear. Both masses were connected by a massless inextensible stem. This idealised model was considered to act as a damped harmonic oscillator, i.e. the larger the displacement the larger the lodging induced force. Furthermore, the induced force was also a function of the applied frequency, i.e. if the force was applied at the plant's natural frequency then the effects experienced by the plant were greater than if the force had been statically applied. Finally, the criteria used to evaluate lodging was the base bending moment, i.e. the applied force multiplied by its point of application from the base.

Baker's 1995 model assumed that the plant could be considered to act in isolation from its neighbours. However, plants of a number of plant species can interact with neighbouring plants at various growth stages (e.g., oil seed rape). In order to take this into account, Baker et al. (2014) subsequently developed a generalized model where such plant interactions were considered. The revised model also contained a more realistic (albeit more complicated) representation of the wind and enabled the failure of the plant to be modelled at any distance along the stem. In addition, the generalised model was able to express failure in terms of risk as opposed to the deterministic framework used in Baker (1995). These modifications enabled the generalized model to be potentially used for a variety of crops. Nevertheless, biological factors including plant morphology, canopy shape, root shape, stem strength etc. vary in different crops and thus the model must be calibrated for each crop.

The relative importance of the plant parameters (i.e. quantitative descriptors of the biological form of the plant) for the generalized model have not been properly investigated in a detailed manner and it is with this which the current paper is concerned. We have chosen to examine oats (*Avena sativa*) in detail as oats have a propensity to lodge (Chalmers et al., 1998; White et al., 2003; Wu and May, 2019) yet there is increasing interest in the cultivation of oats as a result of an increasing appreciation of the health and nutritional benefits associated with the consumption of oat grains (Clemens and Van Klinken, 2014; Thies et al., 2014; Ryan et al., 2017). Additionally, oat plants differ from other cereals as oat panicles act independently as individual shoots (Figure 1a) immediately after panicle emergence but become progressively more interlocked with neighbouring panicles as the crop matures (Figure 1b). This behaviour provides an opportunity to test the generalised model in its entirety. The relevant data required for testing is provided in section 2. Section 3 relates to the parameters used as the model input data, the final effect of these parameters on crop failure and the ability of the model to predict lodging both spatially and temporally. Finally, a discussion about the research outcomes and an overall conclusions are presented in sections 4 and 5 respectively.



(a) (b)

Figure 1. Oat canopies a) at beginning of the lodging season (just after panicle emergence) b) at the middle of the grain filling stage.

2 Material and method

In this section the generalized lodging model proposed by Baker et al. (2014) is briefly outlined (Section 2.1) and the required parameters are classified into two broad groups: agronomic parameters and aerodynamic parameters. For each group, the appropriate approach to measuring the parameters is described (section 2.2 and 2.3).

2.1 The Lodging Model

As outlined above, Baker et al. (2014) developed a generalised crop lodging model capable of predicting lodging in plant canopies (Joseph et al., 2020) and demonstrated that the critical velocities for Stem (U_{Ls}) and Root (U_{LR}) lodging were complex functions of a variety of plant and aerodynamic properties:

$$U_{Ls} = \text{function}(f_n, X, n, \sigma, a, t, x, \rho, A_{CF}, l, I, \theta, \tau) \quad (1)$$

$$U_{LR} = \text{function}(S, d, f_n, \rho, X, A_{CF}, I, \tau, \gamma) \quad (2)$$

where f_n is the natural frequency of the plant, X is the height of the centre of mass of the canopy, n is the number of stem per plant, σ is the stem yield stress, a is the stem radius, t is the stem wall thickness, x is the distance up the stem from the ground, ρ is the air density, A_{CF} is the plant drag area, l is the length of stem, I is the turbulence intensity, θ is the damping ratio, τ is the averaging time for wind loading of the plant, S is the soil shear strength, d is the root plate diameter and γ is a constant. (The exact form of the actual functions can be found in Appendix A.)

The occurrence of lodging is highly dependent on meteorological conditions and the risk of crop failure can be calculated by integrating joint (wind and rainfall) probability density functions (PDFs) (Mohammadi et al., 2018; Mohammadi et al., 2020; Sterling et al., 2018). Figure 2 shows a sample joint probability density function for Ireland using data from 1987 to 2016 for June and July. (The data underpinning is described in detail in section 3.7.). In this figure the vertical axis is the rainfall and the horizontal axis is the wind speed. The contour shows the joint probability density function where each colour reveals a certain range of probability of occurrence for wind and rainfall.

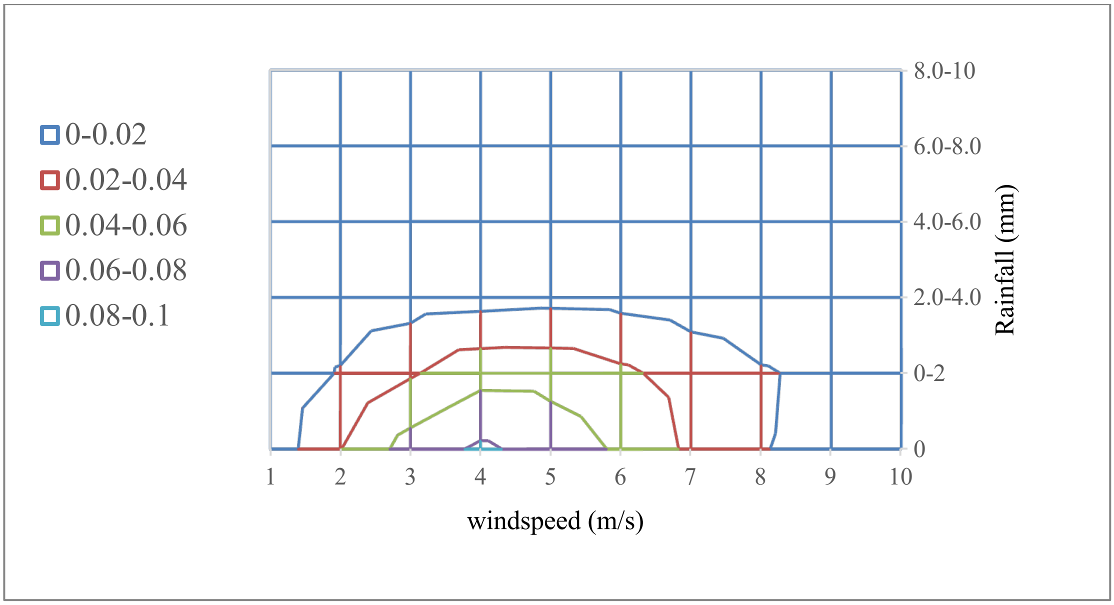


Figure 2. Joint (wind and rainfall) probability density function for cork airport station in Ireland in the period from 1987 to 2016 for June and July

The joint PDF must be integrated in terms of wind and rainfall boundaries where lodging is likely to happen to obtain the lodging risk (Baker et al., 2014). Stem lodging will happen if the wind speed exceeds the required lodging wind velocity (U_{LS}). Root lodging depends on both rainfall and wind speed, where the lower wind speed limit is the saturation velocity (U_s), which is the least velocity required for root lodging (equation 3), and the rainfall "boundary" is defined by equations (3) and (4) (Baker et al., 2014):

$$U_s = U_{LR}(1 - \frac{i_s}{i_0})^{0.5} \quad (3)$$

or

$$i = (1 - \frac{U^2}{U_{LR}^2})i_0 \quad (4)$$

where i_s is the saturation rainfall, i_0 is reference rainfall, which is rainfall at zero wind speed and i is daily rainfall, and U is hourly wind speed. An example of the lodging/no lodging boundary curve (given by equation (4)) as well as lodging likelihood in different wind and rainfall conditions for a sample oat plant (n=1, a=2.5mm, t=0.61mm, l=1.16m, A_{CF}=19.46cm^2, X= 0.59m, d =54.2mm) is shown in Figure 3.

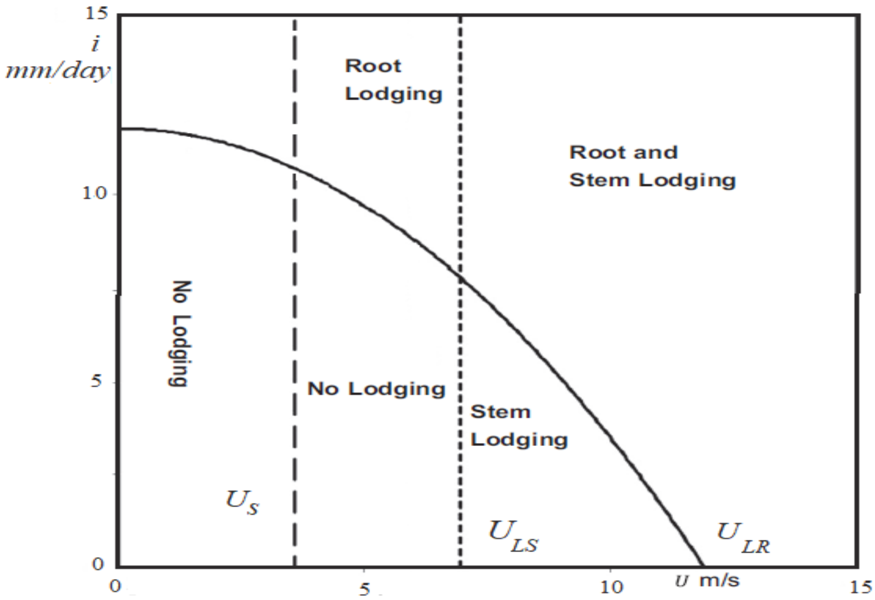


Figure 3. Lodging regions in the daily rainfall / hourly mean wind speed plane

For a full discussion of the derivation behind equations (1) – (4), the reader is referred to Baker et al. (2014). Further details relating to the equations are provided in Appendix A. As stated previously, the aim of this paper is to investigate the relative importance of the plant parameters for oats as opposed to deriving the model.

2.2 Agronomic measurements

2.2.1 The experimental crops

Agronomic experiments were carried out at two different but adjacent sites in the Republic of Ireland in 2017 and 2018. In 2017, field experiments were undertaken at Knockbeg, County Laois (52.86 °N, 6.94 °E, 54 MSL), while in 2018 the relevant data was obtained from experiments conducted at Oak Park Research Centre, County Carlow (52.86 °N, 6.92 °E, 57 MSL). These two locations are approximately 1.5 km apart. For both experiments, the same experimental protocol was followed and the same variety, seed rate, plant growth regulator, Nitrogen timing and Nitrogen rate treatments were used. The experiments were sown in October of the previous year (13^{th} October 2016 and 10^{th} October 2017). In addition to the agronomic measurements, the crops were monitored frequently to identify any lodging event during the period between panicle emergence (growth stage GS51, Zadoks et al., 1974) and before the final harvest (growth stage GS93). Lodging was assessed according to the procedure of Caddicott and Nuttall (1979), which assigned a lodging index from scale of 0 (no lodging) to 100 (completely lodged) and considers both the angle and extent of lodged plants.

The oat varieties used in the experiments were Barra (susceptible to lodging) and Husky (moderate resistance to lodging) (DAFM, 2019). Each variety was grown under a combination of different treatments including low and high seeding rates (200/500 seeds per m^2), the presence or absence of a PGR (Plant Growth Regulator) programme (1l/ha of 'Ceraid' (Taminco BVBA) containing 620 g/l of chlormequat applied in 200 l/ha water at GS30/31, followed by 2l/ha of 'CeCeCe 750' (BASF Plc) containing 750g/l chlormequat applied in 200 l/ha water at GS32), low and high Nitrogen rates (90/180Kg/ha) and early and late Nitrogen timing (the early Nitrogen was applied as a split at GS30 and GS32, and the late Nitrogen was applied split at GS32 and GS39) giving 32 different management treatments. The soil type was a sandy clay loam and the plot size was 12m long and 2.1m wide, plot ends were removed before harvest and a harvested length of 9.6 m taken. Plant counts were taken at GS12-13 before the plants had started to tiller, 3 separate linear row lengths were counted in-situ and corrected to an area based on the row width. In the sampling process, seven plants were taken from each plot and there were three replicates of each treatment (21 samples). Altogether, 1334 samples were collected to provide the agronomic data base (32 (husbandry techniques)× 7 (sample in each sampling) × 3 (sampling times each years) × 2 (years of experimental data)).

2.2.2 Measurements of stem and root parameters

The number of plants per square metre were determined in the month of February after sowing while the number of panicles per square area were counted in situ in each experiment during early June. A selection of plants were carefully excavated to keep the root structure system undamaged and taken to the laboratory. Next, the roots were removed and washed carefully and the root plate diameter were measured. These parameters were measured on a solid rigid portion of the root

(Berry et al., 2000). Moreover, as the roots do not grow uniformly, the largest and smallest values of the root plate diameter in each root were averaged. The main stem was balanced on a ruler and the height of the balance point to the base was measured indicating the centre of gravity. Additionally, the plant height, length of each internode (the distance between two nodes), stem diameter and wall thickness at the second internode were measured.

2.2.3 Measurements of natural frequency

The plant's natural frequency was calculated by counting the oscillations of single shoots over time. In this method, suggested by Berry et al. (2000), in still conditions the shoot should be isolated from other plants and the ear collar displaced by ~10cm from the vertical position and subsequently released. The number of complete oscillations within a given period of time was then recorded. In an ideal conditions this method should be undertaken in the field where the plant was isolated from any other external effects such as other plants and wind, however in practice such conditions were difficult to achieve. Alternatively, plants could be excavated and carried to a laboratory where still conditions could be provided, although the possible effect of anchorage system on natural frequency was neglected by this procedure. A more consistent, albeit more complicated approach was to evaluate this parameter using standard wind engineering methods outlined in section 3.3.

2.2.4 Stem and root strength measurements strength

In addition to the above parameters, the stem yield stress and the root failure moment, were also calculated and measured. For the stem yield stress parameter, the plants had to be examined while they were fresh, as dried shoots usually become brittle which might affect the results. The stem yield stress was calculated using the following equation (Berry et al., 2000):

$$\sigma = \frac{F_s h a}{\pi(a^4 - (a-t)^4)} \tag{5}$$

Where a is the stem radius, t is the stem wall thickness, F_s is the applied force normal to the stem, h is the internode length and σ is the stem yield stress. To determine F_s, the relevant section of the stem is supported at the nodes and the force required to break the stem is applied at the middle of the stem. Full details relating to this experiment are given in Berry et al. (2000).

The root failure moment was measured to obtain a relationship between the anchorage system and the root failure moment. Such an expression for wheat was reported by Ennos (1991) and further investigated by Griffin (1998), which is describes as follows:

$$R_s = \gamma S d^3 \tag{6}$$

Where γ is a constant, S is the soil shear strength and d is the root plate diameter. Accordingly, in keeping with the approach used by Griffin (1998), the ground was wetted to allow the anchorage system to fail during experiments. Next the failure root moment was measured using a torque meter (Mecmesin, Advanced Force and Torque Indicator (AFTI)) and plant samples were carefully excavated and brought to the laboratory, where their root plate diameter was measured (Griffin, 1998; Baker et al., 1998; Berry et al., 2003). Finally, the soil shear strength at the depth of 14 cm was measured using a PILCON shear vane fitted with a 1.9 cm vane. The results of these experiments are presented in section 3. This parameter can also be estimated from the amount of daily rainfall (i) and soil parameters as follows (Baker et al., 1998):

$$S = S_d - \frac{i}{\left(\frac{\rho_s}{\rho_w}\right)(f-w)L} (S_d - S_w) \tag{7}$$

Where ρ_s and ρ_w are soil and water density, f is the water content at field capacity, w is the water content at wilting point and L is the root depth. Moreover, S_d and S_w are the soil shear strength for dry and wet soil respectively and can be derived as follows (Baker et al., 1998):

$$s_w = 1484e^{-5f/c} (2.2 - 0.24v)(4.82c - 0.30) \tag{8}$$

$$s_d = 1125e^{-5w/c} (2.2 - 0.24v)(4.82c - 0.30) \tag{9}$$

Where c is the clay content and v is a visual score measuring soil compaction.

2.3 Experimental setup for aerodynamic parameters

In order to study the aerodynamic parameters required in the generalised model (natural frequency, damping ratio and panicle drag area), a series of measurements were undertaken between 1-15 June 2017 (GS51 to GS75) and 31 May-30 June 2018 (GS51 until the final harvest, GS93). In all cases, the crops studied received standard agronomic treatments representative of normal farm practise. The experimental setup was aimed to observe the interaction of wind on oat plants, where wind data was collected by two 100 Hz sonic anemometers (Gill Instruments Ltd), which were installed at crop height (1-1.5m) and 3m height (Figure 4a). A target plant was selected and its panicle was painted red. The movement of the target plant was recorded by two video cameras (Lorex, LW2770 series) at the crop height (Figure 4b) and post-processed using a video tracking MATLAB code. Additionally, a precipitation sensor (OMC-270) was used to monitor rainfall during the data collection period. Figure 4 shows the experimental setup with further information available in Mohammadi et al. (2019), Sterling et al. (2018) and Joseph et al. (2018).

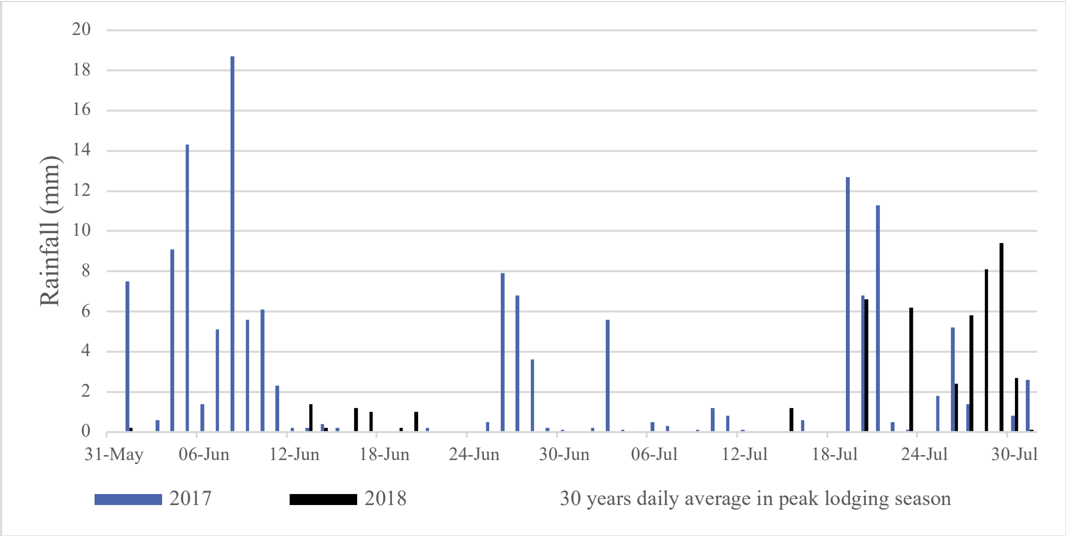
a) Experimental measurements b) Oat target position in front of cameras

Figure 4. The experimental set up used to obtain the aerodynamic parameters for the model.

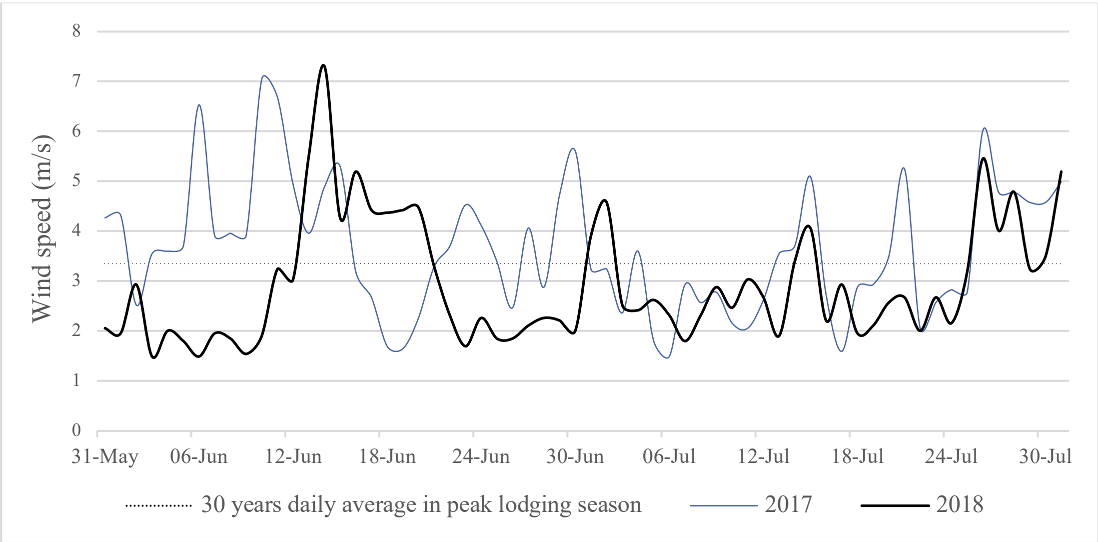
3 Results

3.1 plant parameters

The weather conditions during June and July (which is associated with peak lodging in oats) in the first year (2017) were wet and windy (average daily rainfall was 2.34mm and the mean daily wind speed was 3.6m/s) and five lodging events were recorded during June and July. However, in the second year (2018), the period between panicle emergence and maturity (June and July) was very dry with moderate wind speeds (average daily rainfall was 0.8mm and the mean daily wind speed was 2.9m/s) and no lodging occurred. Figure 5 shows the daily rainfall (figure 5a) and mean daily wind speed (figure 5b) during June and July 2017 and 2018, together with the associated 30 years' averages.



a)



b)

Figure 5. (a) The daily rainfall (b) the mean daily wind speed in the peak lodging season in 2017 and 2018 as recorded in Oak Park meteorological station (Met Éireann, 2019).

Table 1 shows agronomic parameters as measured in 2017 and 2018, together with random uncertainties associated with the measurements which is calculated as $E_{RND} = \pm 2\ S_d/\sqrt{z}$ (Soper, 2014), where E_{RND} is the random uncertainty, S_d is the standard deviation and z is the number of samples. It is noteworthy that the stem yield stress was measured just in 2018 and the natural frequency values provided in this table are measured through counting number of oscillation over time and show $\pm$20% difference with wind engineering approach (section 3.3), which can be the result of neglecting the effect of plant/soil interaction on the dynamic movement.

Table 1. Agronomic parameters as measured in 2017 and 2018.

	2017			2018		
Agronomic parameters	mean	S_d	E_{RND}	mean	S_d	E_{RND}
n	2.03	0.72	0.25	1.27	0.24	0.08
a (cm)	0.32	0.08	0.006	0.28	0.07	0.005
t (cm)	0.09	0.03	0.002	0.09	0.36	0.027
l (cm)	149.18	16.08	1.26	112.40	12.53	0.97
X (cm)	70.19	8.24	1.83	62.54	6.94	1.41
d (cm)	4.97	0.57	0.15	5.29	0.59	0.09
f_n(Hz)	0.8	0.18	0.04	1.20	0.18	0.03
σ (MPa)	-	-	-	40	19.90	5.1

3.2 Soil and anchorage system parameters

In order to determine a relationship between the soil/root ball structure and the moment required for failure, a series of experiments were undertaken as described in section 2.1 to determine the anchorage system failure moment and associated root plate diameter and soil shear strength. In keeping with the approach adopted previously (i.e. equation 6), the data were plotted in a form shown in Figure 6. The slope of the dotted line in Figure 6 (i.e. γ in equation (6)) was ~0.1 which compares with the results of similar analysis for wheat (~0.4; Crook and Ennos (1993), Baker et al. (1998)), barley (~0.6; Berry et al. (2006)) and sunflowers (~0.4, Sposaro et al. (2008)). In the same root diameter and soil condition for different crops, the lower the value of γ, the more susceptible the plant is to root lodging.

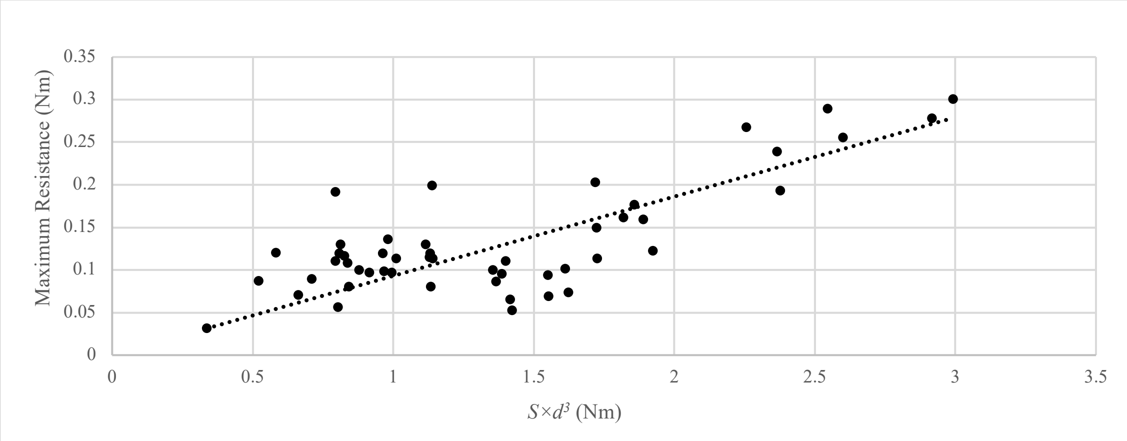
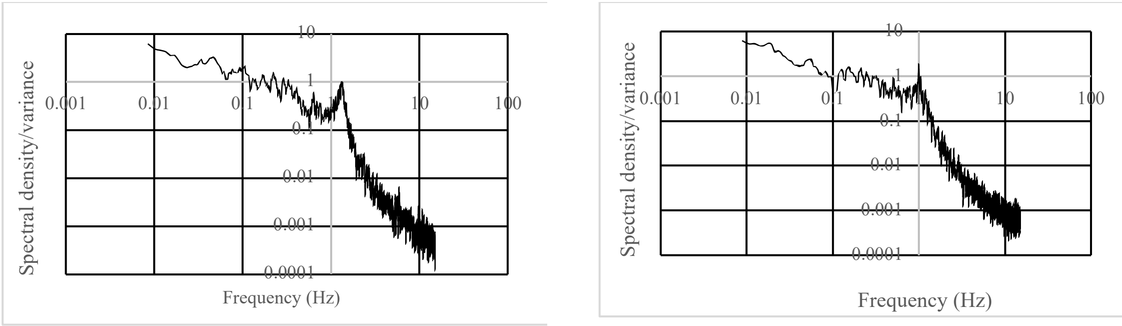


Figure 6. Results of experiments to investigate parameters affecting anchorage system failure moment.

3.3 Frequency domain analysis

The damping ratio and natural frequency can be calculated through a variety of standard wind engineering which were undertaken between 1-15 June 2017 (GS51 to GS75) and 31 May-30 June 2018 (GS51 until the final harvest, GS93). The damping ratio is simply a dimensionless parameter describing how the plant's oscillations decay after a disturbance (Ge and Rice, 2018). This parameter can be calculated by the logarithmic decrement or the transfer function method (Mohammadi et al., 2019; Joseph et al., 2020). A thorough review of both of these approaches and their suitability for the current analysis is given in Joseph et al. (2020), which shows that the value obtained for the current data can vary throughout the season from between 0.06 – 0.16. This is discussed more fully below.

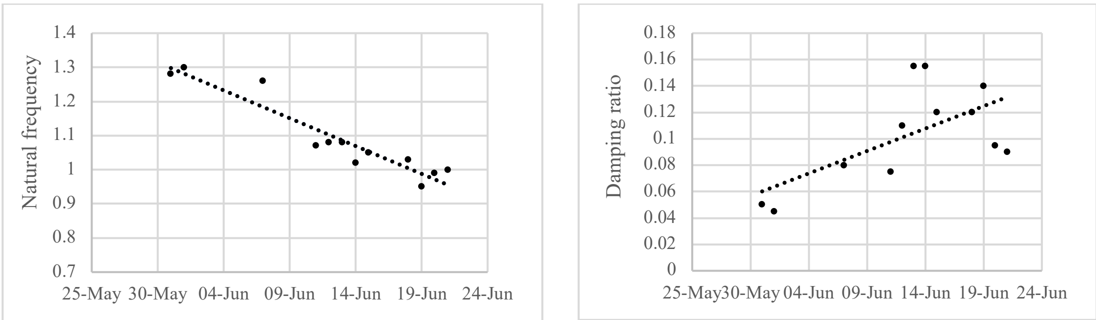
In order to determine the natural frequency of the target plant, the time varying displacement of the plant were recorded as outlined in section 2.3. This displacement was then transformed into the frequency domain using a Fast Fourier Transform (Holmes, 2001) as shown in Figure 7, which illustrates the relationship between the energy content in the oscillation (vertical axis) against the frequency (horizontal axis). In Figure 7, a peak in this distribution is evident between 1Hz – 1.3Hz which corresponds to the plant's natural frequency, i.e. the frequency at which the plant would tend to oscillate if the external force (wind) was not present. At the start of June (Figure 7a) the plants oscillate as single shoots whereas by the end of June (Figure 7b) a degree of plant interlocking has occurred which has decreased the natural frequency. This is important, since as outlined in Sterling et al. (2003), if the energy in the wind was expressed in a similar manner, it would be evident that there is more energy at lower frequencies, i.e., as the magnitude of the plant's natural frequency decreases, the amount of energy available in the wind to load the plant at that frequency increases, which can have important implications form a lodging perspective.



(a) (b)

Figure 7. Crop displacement spectra normalized by variance (a) 1 June 2018 (b) 21 June 2018 (Mohammadi et al., 2019)

Figures 8a and 8b show the variation of natural frequency and damping ratio throughout the relevant lodging period. The figures show that these parameters can change considerably over time. At the start of the season when panicles have just emerged and the plants still act like isolated shoots (31th May and 1st June) the natural frequency is at the highest level, ~1.3 Hz (Figure 8a), and the damping ratio is the lowest level, ~0.05 (Figure 8b). However, as panicles grow and mature through the grain filling stage (7th June afterwards), not only does the weight of the panicles increase but some degree of interlocking between panicles also occurs, both effects result in a decline in natural frequency and an increase in the damping ratio (Mohammadi et al., 2019).



(a) (b)

Figure 8. Variations of (a) Natural frequency (b) damping ratio, during peak lodging season 2018 (Mohammadi et al., 2019)

3.4 Drag Area

The plant drag area parameter (AC_f) is determined by the plant area perpendicular to wind (A) and the drag coefficient (C_f), which can be used to indicate the amount of drag force exerted by wind on the plant. Baker et al. (2014) showed that there is a relationship between the mean plant displacement ($\bar{Y}$) and the mean wind velocity ($\bar{U}$) as:

$$\bar{Y} = \left(\frac{0.5\rho/\mu}{(2\pi f_n)^2}\right) AC_F \bar{U}^2 \quad (10)$$

where μ is the equivalent mass at the top of the plant, producing the same torque as the overall plant's mass does. Assuming values based on agronomic measurements, for the plant height (1-1.5m), and centre of gravity height (0.6-0.8m), as well as plant canopy weight, (50-75 gr) (Finnan, 2018), μ can be estimated. Alternatively, knowing that oat plants during the lodging season usually include 4-6 nodes along the stem, and assuming the mass is equally distributed along the stem, μ can be estimated. Results illustrate that whichever method is used, the value of μ is reasonably consistent (~ 40gr). Figure 9 demonstrates the variation of $K = \left(\frac{0.5\rho/\mu}{(2\pi f_n)^2}\right)\bar{U}^2$ versus the mean displacement where the slope of the curve corresponds to drag area (AC_F~0.021m^2).

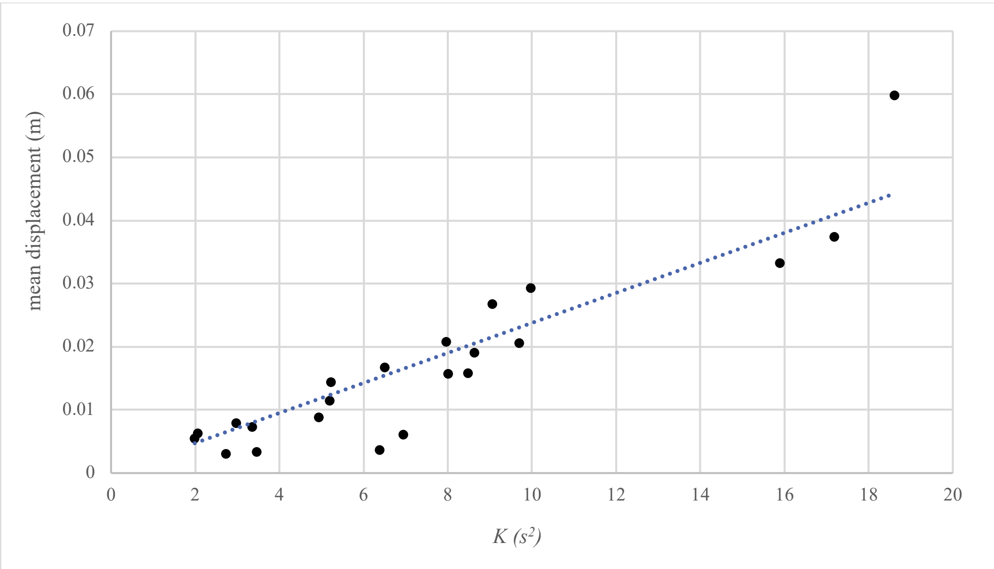
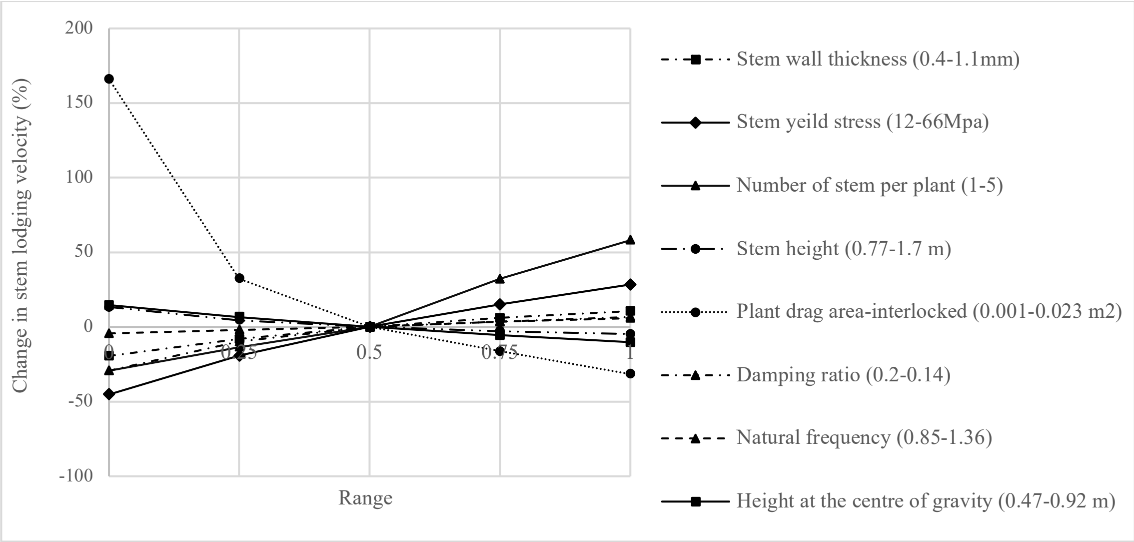


Figure 9. Mean displacement of the target panicle versus $K = \left(\frac{0.5\rho/\mu}{(2\pi f_n)^2}\right)\bar{U}^2$. The Pearson correlation coefficient for the fitted straight line is $R^2 = 0.85$

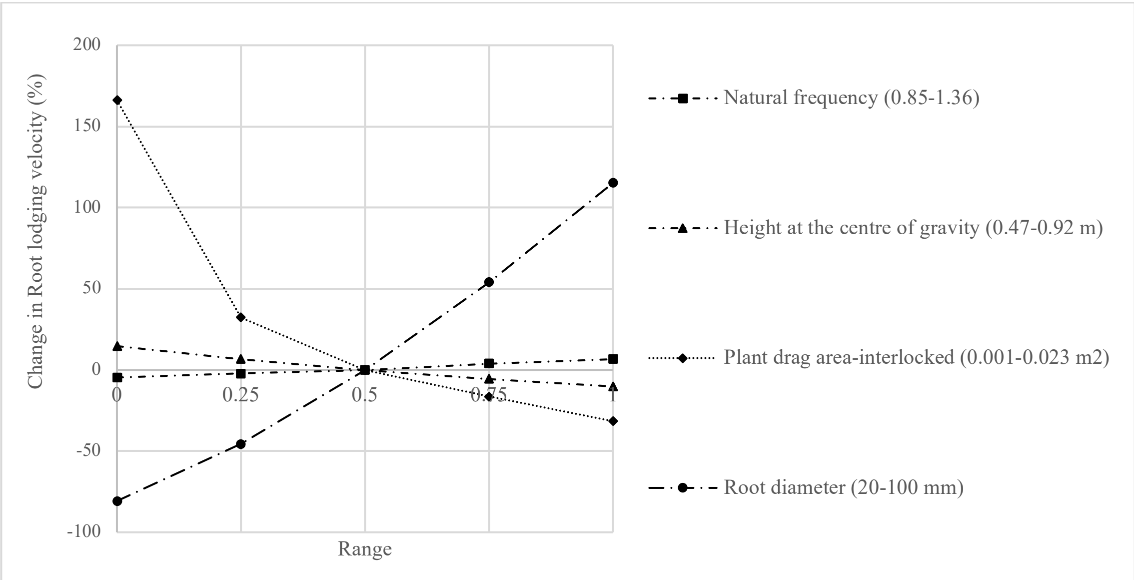
3.5 Parametric analysis

Noting all of the various parameters used in the generalised model (and outlined above), it is worthwhile to examine their relative importance. Thus, Figure 10 shows the results of a parametric analysis which was undertaken to investigate the relative impact of different parameters on the failure wind speed. Each parameter was varied from the lowest to the highest values which were observed during the measurement trials and the percentage of change in the stem/root lodging speed was compared with the mean stem/root failure velocity ($\overline{U}_{LS}$ =6.14m/s, $\overline{U}_{LR}$ =6.80m/s). Additionally, as agronomic parameters were measured in mid-June, the plant parameters variations during the season were also taken into the account to cover all plausible value ranges. Moreover, the panicle drag area was studied for the variations over six interlocked canopies (mean value of AC_F=0.001-0.023m^2), while, the parameter for a single panicle might change from 0.001-0.004m^2.

From Figure 10 it is evident that the plant drag area is the most influential parameter for both stem and root lodging, where the lodging velocity can reduce by three times as panicle becomes interlocked (U_{LS} =4.5-16.34m/s, U_{LR} =4.99-18.11m/s). The lowest range of this parameter is associated with the early peak lodging season when plants have newly emerged panicles. At this time in the growing season, the drag area is low and plants oscillate independently like single shoots. Later during the growing season, as panicles grow and become tangled (interlocked), a higher drag force is exerted on plants, as a consequence, the plant becomes more susceptible to lodging. Notwithstanding this increase in the panicle drag area, the model shows that for the plausible variations associated with a single plant, the stem/root lodging velocity may vary by up to 5-6m/s: U_{LS}=11.03-16.34m/s and U_{LR}=12.23-18.11m/s. Other critical parameters in stem lodging are those which contribute to stem bending strength, (equation A2 in appendix A) including the number of shoot per plant, stem yield stress, radius and wall thickness, respectively ordered by importance. Nevertheless, the latter parameter (stem wall thickness) has a relatively smaller impact (~24 %) on the lodging velocity. The root plate diameter which has a direct effect on anchorage resistance is the second most important parameter in root lodging, and, its effect on the percentage change in root lodging velocity (~115%) is lower than the change influenced by the lowest drag area (~166%). Finally, plant height, centre of gravity, natural frequency and damping ratio have comparatively lower effect in lodging wind speed.



(a)



(b)

Figure 10. Failure wind speeds (a) middle of first internode and (b) anchorage.

3.6 A comparison between model predictions with field observations

Experience has shown that a variety of management techniques can lead to improvements in lodging risk (Berry et al., 2002). In addition, it is also known that the variety type also influences the plant's likelihood to lodge (Griffin, 1998). Work undertaken by (Berry et al., 1998; Griffin, 1998) has led to the concept of a lodging rank, where the impact of variety type and husbandry techniques are expressed in a simple system which indicates the plant's expected propensity to lodge – the lower the rank the more likely the plant is to lodge. Based on the method used by Berry (1998), Baker et al. (1998) and Berry et al. (2000), the oat plants outlined above were grown under different managements which were monitored and assessed for lodging susceptibility during the peak lodging season. For each husbandry technique used, the percentage of lodged area versus time was plotted, and the area under the curve was calculated, indicating accumulated lodged area. Accordingly, all husbandry applications were sorted based on highest (the most susceptible) to lowest (most resistant) lodged managements.

Having calibrated the Baker et al. (2014) generalised model, it is in theory possible to calculate the failure wind speed corresponding to the variety and the impact of relevant different husbandry techniques (variety and treatment) and thus to obtain a model ranking. Accordingly, the model used the agronomic measurements for each treatment to determine the failure stem/root velocity and to calculate the lodging risk.

Figure 11 shows the averaged stem and root lodging velocities as calculated by the lodging model for different managements. All husbandry techniques are abbreviated in the figure where H/B are the plant varieties (Husky/ Barra), 200/500 are the low/high seed rate (200/500 seeds per m^2), Y/N refer to PGR application (Yes/No), 90/180 indicate Nitrogen rate (90/180Kg/ha) and E/L refer to early or late Nitrogen timing. The results show the highest root and stem lodging velocities are 6.6m/s and 9.8m/s respectively.

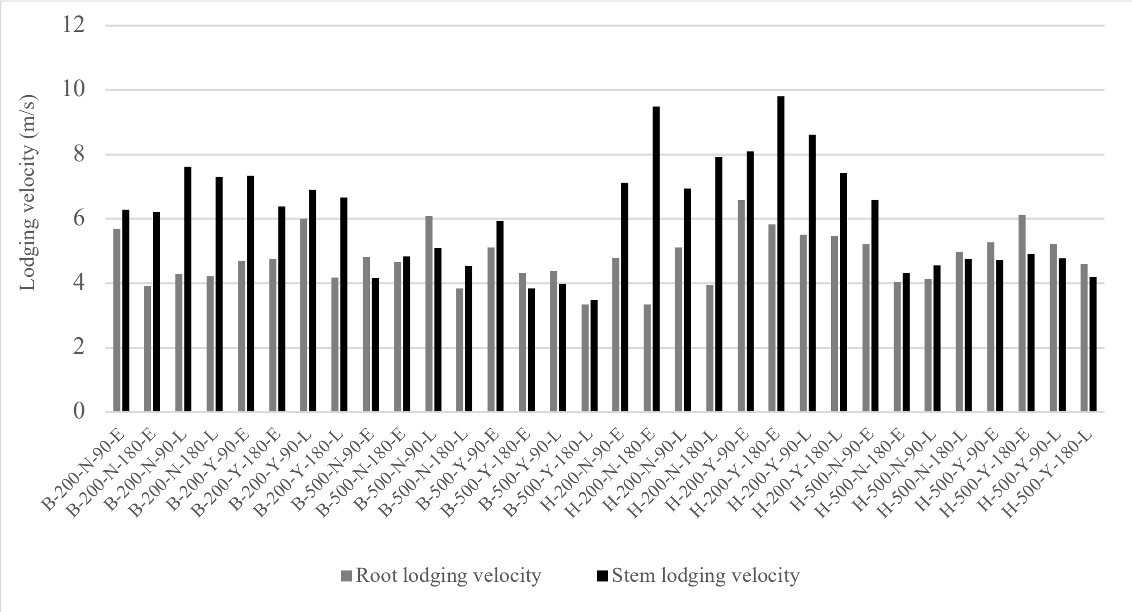


Figure11. Stem and root lodging velocities for different managements

In order to undertake such analysis, it was assumed that the number of panicles (*N*) which interlock together through the season is five on average and that the mean soil shear strength is 25kPa. The soil shear strength was highly dependent on the soil moisture and consequently the amount of rainfall. Hence, due to potential of highly localised differences in soil strength. Whilst both of these assumptions are subjective, they are felt on average to be reasonable and consistent with the experimental data (although this will be explored in more detail below). Figure 12 illustrates the model ranking against the experimental ranking and it can be observed that there is, in general, a reasonable agreement (R^2 = 0. 62) between the two processes.

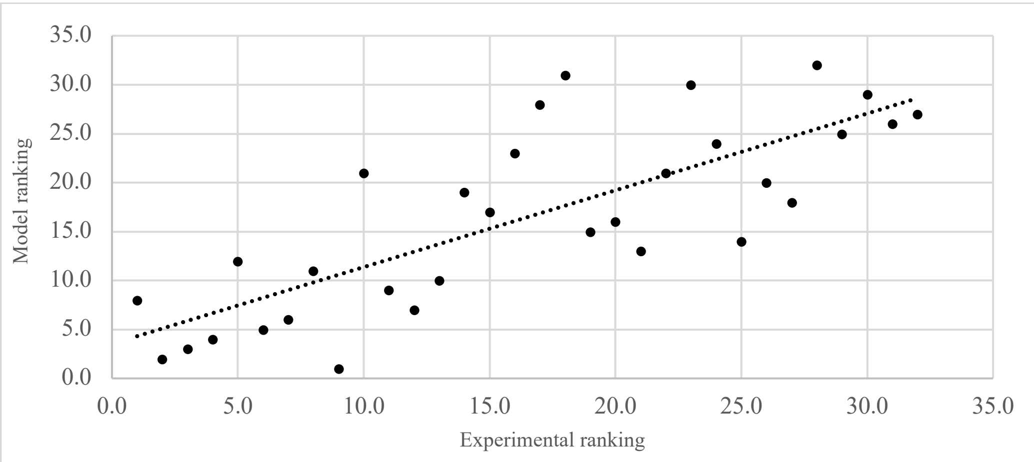


Figure 12. Experimental versus model predicted ranking of lodging susceptibility of 32 management of oat crops (rank 1 is the most susceptible). *S*=25 kPa,

Now, we return to the rather subjective assumptions concerning the number of panicles and soil shear strength noted earlier. A sensitivity analysis was developed to examine the effect of potential changes in these parameters on the model ranking, as variation in these parameters can affect the lodging risk and consequently might change the overall model ranking. Thus, the data in Figure 12 was analysed for different values of soil shear strength and the number of interlocked panicles and the relevant R^2 value (coefficient of determination) determined - the higher value of R^2 indicates the model ranking better agrees with the experimental ranking, showing associated assumptions better describe the reality. Accordingly, results indicates a higher coefficient of determination when it is assumed that 4-5 panicles interlock and 15-30 kPa soil shear strengths. Both of these findings agree well with agronomic observations and field measurements. Interestingly, the model shows a very low R^2 value for single shoots which indicates the importance of taken into account panicle interlocking.

The generalised lodging model can also be used to predict the lodging timing during the peak lodging season (i.e. through the known variations in model input data with respect to time). To compare the model outputs with real observed lodging data (described in section 3.1), all treatments were classified into four groups including, high risk, moderate high risk, moderate low risk and low risk. This classification was based on the recorded accumulated lodged area through the season. Later the model was used to quantify the lodging risk for eight treatments in each class which were ultimately averaged to indicate the risk of lodging for each group. Table 2 indicates treatments and agronomic values of each group as well as the average lodging risk predicted by the lodging model for each class.

Table 2. Agronomic treatments and parameters as measured in 2017 and the lodging risks as calculated by the calibrated lodging model for oats.

	high lodging risk	Moderate-high lodging risk	Moderate-low lodging risk	Low lodging risk
Treatments	B-500-N-180-E	H-500-N-180-L	B-200-Y-180-L	B-500-Y-90-E
	B-500-N-180-L	B-500-N-90-L	H-200-Y-180-E	H-200-N-90-L
	B-200-N-180-E	B-500-N-90-E	B-200-Y-180-E	H-200-Y-90-E
	B-500-Y-180-L	H-200-N-180-L	H-200-Y-180-L	B-200-Y-90-E
	B-200-N-180-L	H-500-Y-180-E	H-500-N-90-L	B-200-Y-90-L
	B-500-Y-180-E	B-200-N-90-E	H-200-N-90-E	H-500-Y-90-E
	H-500-N-180-E	H-500-N-90-E	B-200-N-90-L	H-200-Y-90-L
	H-200-N-180-E	H-500-Y-180-L	B-500-Y-90-L	H-500-Y-90-L
Average Lodging risk	69%	59%	55%	48%

Agronomic parameters	mean	S_d	mean	S_d	mean	S_d	mean	S_d
n	1.90	0.77	1.75	0.72	2.37	0.80	2.06	0.59
a (cm)	0.33	0.05	0.32	0.06	0.34	0.06	0.33	0.06
t (cm)	0.09	0.04	0.09	0.02	0.09	0.03	0.09	0.02
l (cm)	157.64	13.76	151.72	17.33	149.77	12.64	138.06	13.82
X (cm)	76.06	8.18	70.90	7.44	71.50	5.81	64.43	7.85
d (cm)	4.78	0.17	5.17	0.16	4.85	0.14	5.05	0.25
f_n(Hz)	0.76	0.23	0.70	0.10	0.80	0.17	0.89	0.17

In keeping with the approach of Berry et al. (2003), a database of 1000 plants were randomly generated based on mean values and standard deviations of agronomic parameters, assuming the parameter values are normally distributed. Additionally, plant parameters variations through the season were taken into the account and the lodging velocity for each plant was calculated. Next, weather data for the site was extracted from Oak Park weather station (Met Éireann, 2019) located at approx. 1.5 Km from the site and the maximum hourly wind speeds for five lodging event through the season were extracted. Comparing this wind speed with stem/root lodging velocities would suggest if the plant would fail/resist in the lodging event and indicates the percentage of lodged plants, which can be compared with real observations. Moreover, soil shear strength was measured at the field with a shear vane as described in section 2.2.4 and the variation of the parameter through the season was estimated based on equation (7) to (9). The rainfall data was extracted from Oak park metrological station (Met Éireann, 2019) and the soil parameters used in the calculation process were c=0.25, υ =5, w=0.15, f=0.27 (Baker et al., 1998; Teagasc Oak Park, personal communication, 2018). Nevertheless, the model output for the percentage of area lodged is not very sensitive to variation of this parameter. Furthermore, for a wide range of plausible values for soil shear strength in each day, the percentage of area lodged would not change dramatically (less than 20 %).Figure 13 shows a comparison of the lodging percentage by the model and those observed in reality. As the panicles emerged at the beginning of June, panicles were not interlocked in the first two lodging events (1^{st} and 7^{th} June) and the interlocking assumption (N=4, where N the number of panicles which interlock together) was applied from the third lodging event (21th June). In this figure treatments groups (high risk, moderate high risk, moderate low risk and low risk) are as described in table 2.

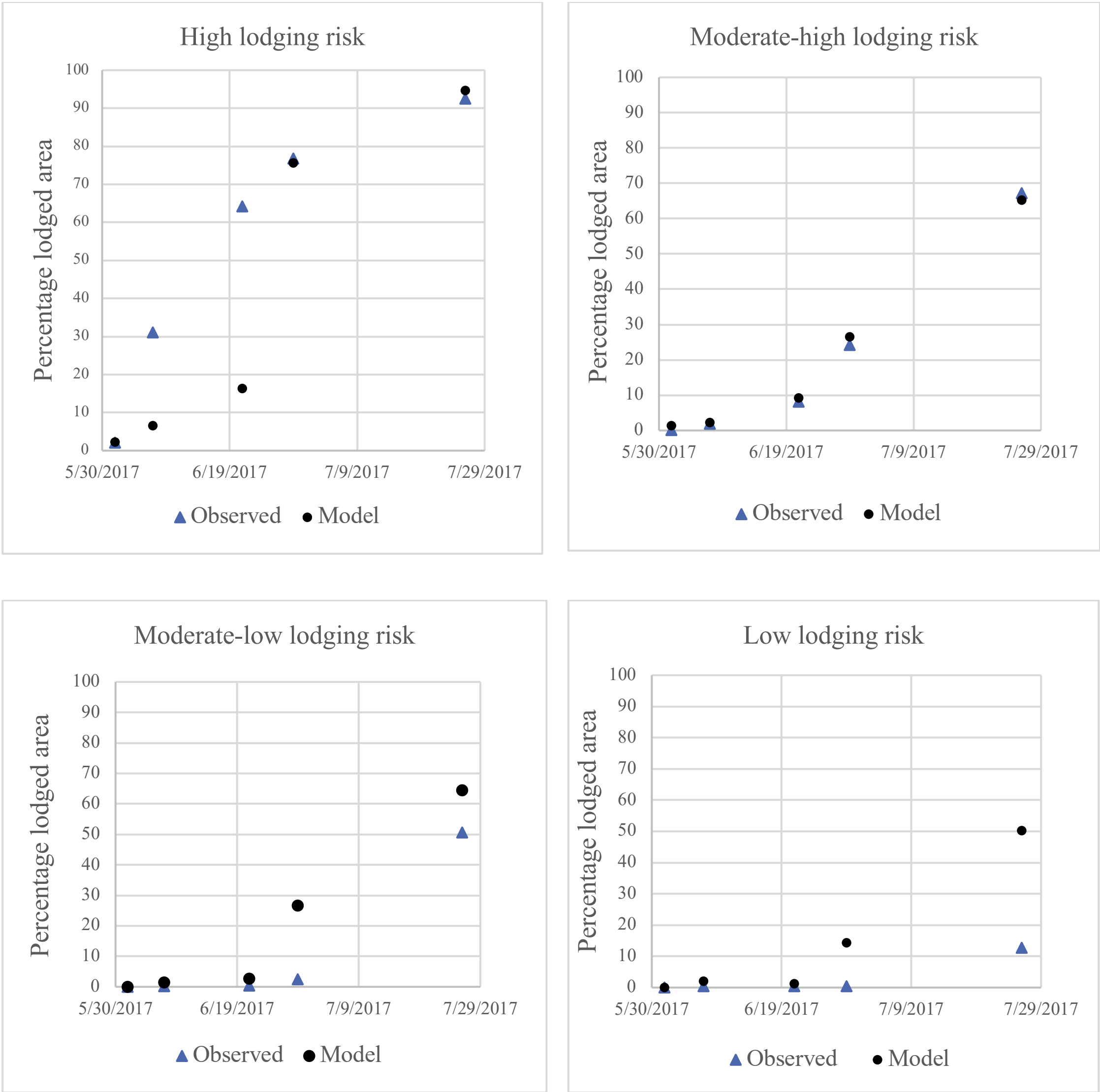


Figure 13. The percentage lodged area in five lodging events as observed experimentally and predicted by the model with high, moderate-high, moderate-low, low lodging risk

Figure 13 shows at the first two lodging events when panicles have just emerged and interact as single shoots with wind, the percentage of lodged area is low and the model predictions are reasonably consistent with reality, although this is not true for the high lodging risk which is under-predicted. The Figure also indicates although there is an element of under prediction in high lodging risk class (a) in the middle of the season, the total amount of lodging is reasonably well predicted in two higher lodging risk classes (a and b) but, over predicted in two lower risk groups (c and d). Two medium lodging risk (b and c) are reasonably well predicted all through the season, although there is a sign of over prediction in the last lodging events. It is noteworthy that this acceptable agreement between model outputs and the experimental data can be found at *N*=4 and 5, while the accumulated lodged is projected slightly higher (~ 4-16%) using the latter assumption. This finding agrees with what is suggested by model ranking and demonstrates the model can best represent lodging assessments assuming four/five panicles create a canopy during tangling period.

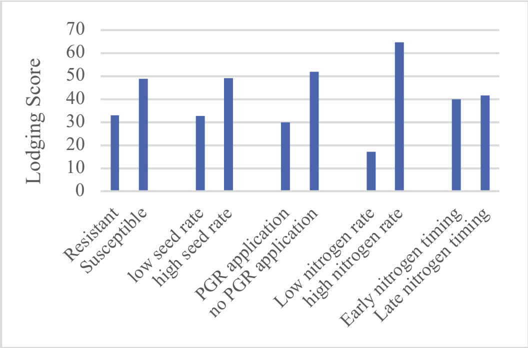
3.7 The effect of agronomic practise on failure wind speeds and lodging

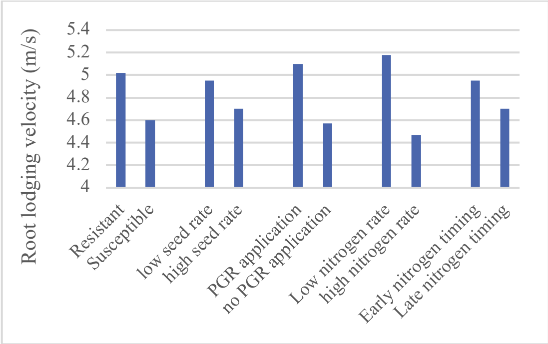
As described in section 2.2, crops were grown under combinations of different agronomic treatments (varieties, Nitrogen timing and rate, PGR application and seed rate). In this section the effect of these treatments on lodging occurrence and associated plant parameters is discussed.

Figures 14a to 14f illustrate lodging scores and velocities for plots which received specific husbandry factors as well as plant parameter associated with lodging. The figure shows choosing a resistant variety rather than a susceptible variety as well as a low seeding rate rather than a high seeding rate reduced the lodging score (Figure 14a) and increased both root and stem lodging velocities (Figure 14b and 14c). The reason of higher resistance in Husky variety and crops grown under low seeding rate treatment can be found in plant parameters associated with lodging. Figure 14d shows resistant variety (Husky) plants had a high root plate diameter, something which appears to be encouraged by a low seeding rate. Similarly, Figure 14e illustrates that stem bending strength was much lower in the high seeding rate treatments than in the low seeding rate treatments and was greater in the resistant variety than in the susceptible (Barra) variety. On the other hand, the resistant variety and low seeding rate treatments also increased panicle drag area to same extent (Figure 14f).

Crops receiving PGRs had a lower lodging scores than crops which did not receive PGR and lodging scores in low Nitrogen rate crops was less than plants receiving high Nitrogen rate (Figure 14a). Moreover, the root lodging velocity was dramatically increased (Figure 14b) whereas the stem lodging velocity was not greatly affected by the use of PGR or the rate of Nitrogen (Figure 14b). This is because PGR application and low Nitrogen rate increased the average root plate diameter (Figure 14d) but led to a decrease in the stem bending strength (Figure 14e) and reduced the panicle drag area and the external bending moment applied on the plant (Figure 14f).

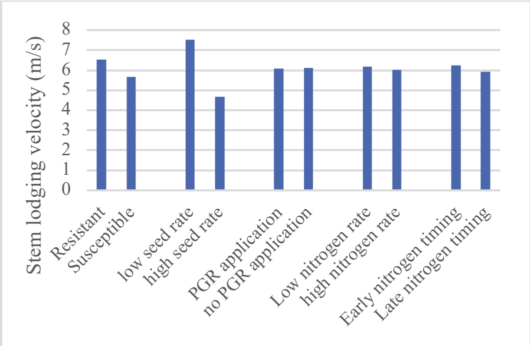
Changing the timing of Nitrogen fertilization did not have a large effect on incidence of lodging (Figure 14a), on lodging velocities (Figure 14b and Figure 14c) or lodging characteristics (Figure 14d-f). Overall, using a resistant variety, a low seed rate, PGR application and low Nitrogen rate can reduce the lodging (Figure 14a) which is consistent with the literature (Wu and Ma, 2019; Berry et al., 2000; Berry et al., 2004). Moreover, the amount of Nitrogen rate and Nitrogen timing are the most and the least influential husbandries to affect lodging susceptibility, respectively (Figure 14a).

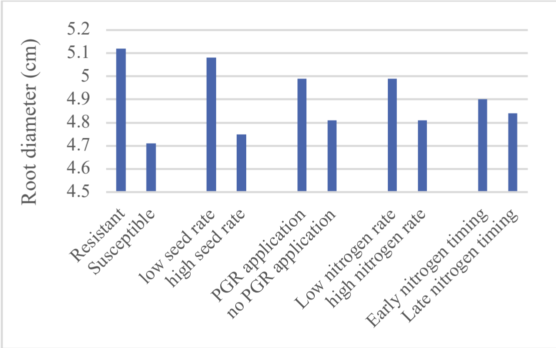




(a)

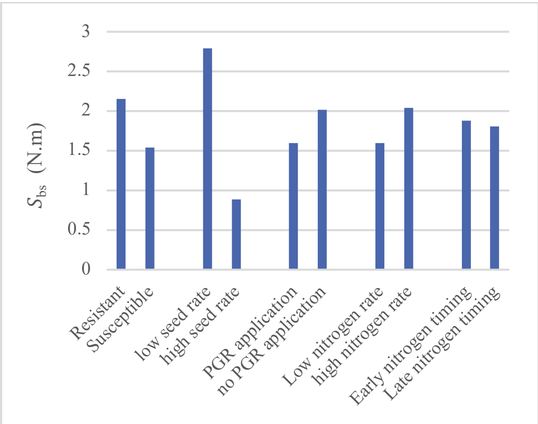
(b)

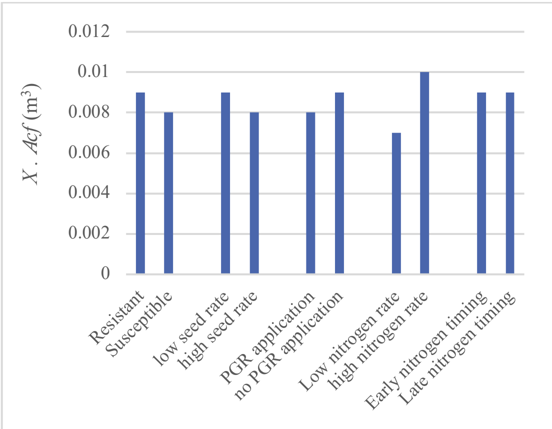




(c)

(d)





(e)

(f)

Figure 14. The effect of different husbandries on the average (a) Lodging score (b) Stem lodging velocity (c) Root lodging velocity (d) root plate diameter, (e) stem bending strength, (f) panicle drag area cross centre of gravity

Table 3 provides further statistical information about the effect of different treatments on lodging scores/velocities and the crop characteristic associated with lodging. Accordingly, mean and the standard error of difference between two mean values (SE_d) are presented. It should be noted that $SE_d = \sqrt{\frac{S_{d1}^2+S_{d2}^2}{z}}$, where S_{d1}^2 and S_{d2}^2 are the variance of first and second treatments and z is the sample size, where z is the same for all treatments (Burns and Dobson, 1981). In order to investigate if the difference between two mean values was statistically significant a parameter, Z, is presented in table 3 which is defined as $Z = \Delta M / SE_d$, where ΔM is the difference between two mean values (Burns and Dobson, 1981). If $2.57 < Z < 3.29$ the two samples are statistically significant at $P < 0.01$ and if $Z > 3.29$ the samples are statistically significant at $P < 0.001$, while, $Z < 1.96$ shows the treatments do not have a significant effect of the properties and two samples are the same (Burns and Dobson, 1981). The Z values provided in Table 3 illustrate that the effect of PGR application and Nitrogen rate on stem lodging velocities was not significant. Similarly, the timing of Nitrogen application did not influence the plant parameters and the incidence of lodging. However, Z values of crop characteristics and lodging scores/velocities receiving other treatments showed their mean values are statistically significant ($P < 0.01$ or $P < 0.001$), which agrees with what has been concluded from figure 14.

Table 3. Mean, SE_d and Z values for different treatments

	Lodging score			Root lodging velocity(m/s)			Stem lodging velocity (m/s)		
	mean	SE_d	Z	mean	SE_d	Z	mean	SE_d	Z
Resistant	32.98	5.14	3.09[1]	5.02	0.15	2.80[1]	6.52	0.23	3.73[2]
Susceptible	48.87			4.60			5.66		
Low seed rate	32.71	5.02	3.27[1]	4.95	0.1	2.50[1]	7.51	0.27	10.51[2]
High seed rate	49.14			4.70			4.67		
PGR application	29.93	7.4	2.97[1]	5.10	0.16	3.31[1]	6.07	0.26	0.15
No PGR application	51.92			4.57			6.11		
Low nitrogen rate	17.20	5.03	9.43[2]	5.18	0.20	3.55[2]	6.17	0.14	1.14
High nitrogen rate	64.64			4.47			6.01		
Early nitrogen timing	40.08	7.92	0.21	4.95	0.26	0.96	6.25	0.22	1.45
Late nitrogen timing	41.76			4.7			5.93		
	d (m)			*S*bs (N.m)			X.ACF (m3)		
	mean	SE_d	Z	mean	SE_d	Z	mean	SE_d	Z
Resistant	5.12	0.09	4.55[2]	2.15	0.19	3.21[1]	0.009	0.0002	5.00[2]
Susceptible	4.71			1.54			0.008		
Low seed rate	5.08	0.08	4.12[2]	2.79	0.28	6.78[2]	0.009	0.0003	3.33[2]
High seed rate	4.75			0.89			0.008		
PGR application	4.99	0.06	3.00[1]	1.60	0.14	3.00[1]	0.008	0.0003	3.33[2]
No PGR application	4.81			2.02			0.009		
Low nitrogen rate	4.99	0.06	3.00[1]	1.60	0.14	3.14[1]	0.007	0.0004	7.5[2]
High nitrogen rate	4.81			2.04			0.010		
Early nitrogen timing	4.90	0.06	1.00	1.88	0.27	0.25	0.009	0.0004	0
Late nitrogen timing	4.84			1.81			0.009		

[1] statistically significant at $P < 0.01$

[2] statistically significant at $P < 0.001$

The agronomic data base shows plant parameters associated with stem and root resistance can vary in a wide range (*n*=1-5; *a*=0.2-0.4cm; *t*=0.04-0.1cm and *d*=2-10cm). Accordingly, the model outputs demonstrated that in the highest bending moment (AC_f=0.023m^2, *X*=0.92m), the failure velocity can changed dramatically from the most susceptible to most resistant plant (U_{LS}=1.98-11.32 and U_{LR}=0.90-9.94). Thus, lodging proof ideotypes should have strong stems (stem radius of 0.4cm and stem wall thickness of 0.1cm) and wide root systems (10cm). The achievement of such breeding targets would represent an alternative means of minimising lodging in oat crops.

4 Discussion

For the first time, a parametric analysis of the generalised lodging model has been undertaken for oats, this has involved examining both the variation in plant parameters that can be expected to occur in typical conditions as a result of different husbandry as well as the corresponding variation of aerodynamic parameters. The analysis has revealed that the drag area is the major parameter in the stem lodging, which is mainly the result of panicle interlocking. Consequently, panicle entanglement through the season, which results in larger drag area, increases the risk of lodging. Additionally, parameters related to stem bending strength including the number of stems per plant, stem yield stress, stem radius and wall thickness were found to be the next important factors for the stem lodging. The most influencing parameter in stem lodging has been found to be different for oats when compared to say, wheat (Berry et al., 2003), sunflower (Sposaro et al., 2010) and barley (Berry et al., 2006), however, the stem bending strength factors (i.e. stem wall thickness, stem diameter etc.) have been persistently reported to have a high importance. On the other hand, factors like natural frequency and the height of center of gravity were found to have relatively small influence on stem and root velocities (Berry et al., 2003; Sposaro et al., 2010). Comparing average values measured for oats (Table 1) with similar measurements in wheat (Berry, et al.. 2003) indicates that although wheat plants can have a higher number of stem per plants (3.2), other parameter related to the stem bending strength including stem yield stress (30MPa), stem wall thickness (0.64mm) and the stem radius (1.67mm) are lower than what has been measured for oats, resulting in a lower average stem lodging ($\overline{U}_{LS}$ =4.34m/s) for wheat at the stem base.
Similar to stem lodging, the drag area is the most influential parameter in oat root lodging. Moreover, the root plate diameter, which is associated with root resistance was identified as the second major factor in root lodging. Interestingly, this parameter was also reported as the major influencing factor in root lodging in other crops including wheat (Berry et al., 2003), barley (Berry et al., 2006) and sunflower (Sposaro et al., 2010). Nevertheless, experimental results acknowledged previous belief about weakness in the oat anchorage system (Hamilton, 1951; Wu and Ma, 2019), where the root system of oats was found to be more susceptible to lodging due to a lower R_s/Sd^3 ratio in comparison to other studied crops (Crook and Ennos, 1993; Baker et al., 1998; Berry et al., 2006; Sposaro et al., 2008). The R_s/Sd^3 (in the equation 6), shows the anchorage failure moment for a specific soil shear strength and root diameter. Thus, the lower the ratio is, a lower moment is required to fail the anchorage system. It is noteworthy that, although average values reported for root plate diameter (~40mm) in wheat (Berry et al., 2003; Berry et

al., 2000; Griffin 1998) were lower than values measured in this research (Table1), due to stronger anchorage system in wheat (higher γ value), the average root lodging velocity for wheat (10m/s) is higher than oats (6.80m/s). Although this research showed the failure moment is related to the root diameter in oats (equation 6), more studies are recommended to investigate other factors (e.g. root depth, stiffness etc.) which can be potentially effective on the anchorage system resistance in oats and other crops.

This research showed interlocking is a dominant factor in the oat lodging process, which increases the drag area dramatically. As the wind induced force applied on the crop is proportional with the panicle drag area, interlocking has a profound effect on the drag force applied by wind. Consequently, the susceptibility of oats increases during June and July as panicles grow and become interlocked. It was also found the plant's growth during lodging season which results in heavier panicles and interlocked canopies reduces the natural frequency and increases the damping ratio in the shoot. Nevertheless, both these parameters were found to have a very slight effect on lodging velocity. Additionally, although the entanglement affects the oat plant oscillation, the shoot's natural frequency can be detected all through the season. In the case of the other crop which create tangled canopies, oil seed rape, the tangling effect is much more pronounced, where the natural frequency is less detectable and the damping ratio is much higher (~0.2) (Joseph et al., 2020).

The lodging risk is dependent on both plant susceptibility and adverse weather conditions. As shown in Figure 2, the hourly wind speed and rainfall are weekly, if at all, correlated. Mohammadi et al. (2018 &2020) showed, for the peak lodging season (June and July) in Ireland and the UK, a double exponential and Weibull distributions can represent rainfall and wind PDFs respectively. Interestingly, the probability of wind speeds greater than 9m/s is very low and any plant management or genetic manipulation moving the lodging wind speed to such values can dramatically reduce the likelihood of lodging. In this study, we found that choice of variety and crop management could increase stem lodging velocity to values greater than 9m/s. However, plant structures with similar lodging velocities could also be achieved through plant breeding.

The model was used to identify values of parameters related to stem/root resistance that can dramatically reduce the risk of lodging. These findings can help plant breeders to breed lodging resistant plants/treatments and helps them to better target crop husbandry inputs to increase lodging resistance. Additionally it was found that stem lodging can be reduced by good husbandry increasing the lodging velocity to values higher than 9m/s, while none of husbandries were found to be effective enough to increase root lodging velocity to values with very low probability of occurrence (higher than 8 or 9m/s). Nevertheless, the model shows that increasing the root plate diameter to the highest plausible values can enhance the root lodging velocity to 9.6m/s, providing a target for plant breeders.

5 Conclusion

A calibrated oat lodging model has been used to investigate the relative importance of a variety of environmental factors and plant parameters. The following conclusions can be made:

- The model can predict the lodging timing and quantity during the lodging season, although there is a sign of over prediction for low risk managements.
- Panicle interlocking affects dynamic movements of the plants and increases the drag area and the lodging risk. Moreover, it is a key factor for the model to predict lodging quantity and timing. Besides, the number of stems per plant, stem yield stress, stem radius and wall thickness for the stem lodging and the root plate diameter for the root lodging were also found to be important factors.
- Even in adverse weather conditions and high panicle interlocking, lodging can be avoided to a high extent by targeting stem and root resistance parameters. Additionally, using a resistant variety, a low seed rate, PGR application and low Nitrogen rate were found influential treatments to reduce lodging.
- Anchorage system in oats was found to be weaker than other crops, suggesting plant breeders and genetic experts to increase the root plate diameter to reduce like hood of root lodging.

6 Acknowledgements

This paper is dedicated to one of the authors, John Finnan, who died in an aircraft accident during the course of the research. John's expertise and input was instrumental for the agricultural elements of the research. However, John also had an uncanny knack of delivering a constructive and well-timed challenge on the meteorological aspects of the research, thereby ensuring that those authors who claim to profess such expertise reflected long and hard on how their message could be delivered more appropriately - something which is key to ensuring successful transdisciplinary research. Perhaps, this is something that we all might like to reflect on as subject boundaries become less opaque - he would have liked that.
The first author would also like to thank the Walsh Fellowship whose funding made this research possible.

7 Appendix A. Lodging velocities equations

Based on failure bending moments, failure wind speeds for the stem known as stem lodging velocity (U_{LS}) can be obtained as (Baker et al., 2014):

$$U_{LS} = \left(\frac{(2\pi f_n)^2\left(\frac{X}{g}\right) S_{bs}}{\left(1+(2\pi f_n)^2\left(\frac{X}{g}\right)\right)(0.5\rho A_{CF}X)(\cos\left(\alpha\frac{x}{l}\right)-cot\alpha \sin\left(\alpha\frac{x}{l}\right))(1+ I \left(4g_{MB}^2+g_{MR}^2(\frac{\pi}{4\theta})\right)^{0.5}}\right)^{0.5} \quad \text{(A1)}$$

Where S_{bs} is the stem bending strength and is defined as follows (Baker et al., 2014):

$$S_{bs} = \left(\frac{\sigma\pi a^3}{4}\right)\left(1 - \left(\frac{(a-t)}{a}\right)^4\right)n \quad \text{(A2)}$$

α is a dimensionless parameter which can be estimated as:

$$\alpha = \frac{3}{(2\pi f_n)^2(\frac{X}{g})} \quad \text{(A3)}$$

Two other parameters used in equation (1) are g_{MB} and g_{MR} which are the gust factor of broad banded stem moment and the gust factor of resonant stem moment respectively, defined as follows (Baker et al., 2014):

$$g_{MB} = 0.42I \ln\left(\frac{3600}{\tau}\right) \quad \text{(A4)}$$

$$g_{MR} = (2\ln(3600f_n))^{0.5} + \frac{0.577}{(2\ln(3600f_n))^{0.5}} \quad \text{(A5)}$$

Root lodging velocity can be derived as follows (Baker et al., 2014):

$$U_{LR} = \left(\frac{R_s}{\frac{((1+(2\pi f_n)^2\left(\frac{X}{g}\right))}{(2\pi f_n)^2(\frac{X}{g})}(0.5\rho A_{CF}X)(1+2Ig_{MB})}\right)^{0.5} \quad \text{(A6)}$$

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