Development and application of a model for calculating the risk of stem and root lodging in maize

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Abstract

Lodging is a major constraint to increasing the global productivity of maize (*Zea Maize* L.). The objectives of this paper are to: i) describe a model for stem and root lodging in maize, ii) calibrate the anchorage strength component of the model, iii) evaluate the model's applicability by assessing its capacity to explain effects of crop husbandry on lodging risk and iv) investigate the potential to further develop the lodging model to predict lodging risk at an early enough growth stage for tactical agronomic action to minimise lodging risk. The study involved a

25 multidisciplinary collaboration between crop scientists, wind engineers and geospatial

26 scientists in the UK and China. Three field experiments with plant population density and

27 nitrogen (N) fertiliser rate treatments were conducted in the UK and China to develop and test

28 the lodging model. Plant characteristics associated with lodging were measured in the

29 experiments after flowering. An existing model of cereal anchorage strength that uses the

30 spread of the root plate as its primary input was demonstrated to be applicable for maize and

31 calibrated for this crop species. The lodging model's predictions of the effects of plant

32 population and N fertiliser on lodging risk were consistent with published observations. The

33 lodging model calculated that increasing the plant population significantly reduced the

34 anchorage and stem failure wind speeds in all experiments, thus increasing the risk of lodging.

35 This effect was primarily due to increased plant population reducing the spread of the root plate

36 and the stem strength. Changes in N fertiliser had a smaller effect on the lodging associated

37 plant characters. A sensitivity analysis showed that stem failure wind speed was influenced

38 most by variation in stem strength and root failure wind speed was influenced most by variation

39 in the spread of the root plate. This study has shown that the leaf area index measured at leaf

40 4, 6 or 8 stages is a good indicator of a crop's future risk of lodging, which demonstrates the

41 potential to develop the model into a practical tool for predicting lodging risk in time for tactical

42 agronomic decisions to be made during the crop's growing period.

43

1. Introduction

Lodging is defined as the permanent displacement of plant stems from their vertical position (Berry et al., 2004). Lodging is a major problem in Maize (*Zea Mays* L.) and has been estimated to account for global yield losses of between 5% and 20% per year for this crop (Flint-Garcia et al., 2003; Hu et al., 2013). This amounts to a cost of lost production of approximately \$7.5 to \$30 billion per year based on gross production figures in 2004-6 (http://www.fao.org/home/en/). It has been reported that lodging can reduce maize yield by 14-28% when it occurs during the 12-leaf stage, and by 30–48% when it occurs during grain-filling (Li et al., 2015a, b). In addition to yield loss, lodging reduces grain quality and increases the time to harvest and drying costs (Kamara et al. 2003; Huang et al. 2015). Lodging is a particular challenge in maize because increasing plant density increases both yield and lodging susceptibility (Xue et al., 2017).

Maize lodging has been shown to result from buckling of the stem (stem lodging) (Hu et al., 2013) or failure of the anchorage system (root lodging) (Fincher et al. 1985; Kamara et al. 2003). Previous studies of maize lodging have generally focussed on specific components of the lodging process, e.g. the stem strength or rind penetration resistance (Colbert et al., 1984; Li et al., 2014), or have not accounted for the dynamic nature by which the plant interacts with the wind (Guo et al., 2019) or rely on generating artificial wind with a mobile wind machine which does not take into account the appropriate turbulence characteristics of the wind (Wen et al., 2019). However, to fully understand how factors influence both stem and root lodging it is necessary to integrate all the key processes including: the dynamic interactions between the plant and wind, the strength of the stem and the strength of the anchorage system. A comprehensive lodging model has been successfully developed for cereal plants (Baker et al., 2014; Berry et al., 2003). This model assumes that the unit of lodging is a single plant and stem lodging is expected if the wind-induced bending moment

69 (leverage) of the shoot exceeds the stem failure moment, and root lodging is expected if the

70 leverage force of the plant exceeds the anchorage failure moment. Recently the aerodynamic

71 properties of plants have been ascertained experimentally (Joseph et al., 2020) which enables

72 the cereal lodging model to be developed to better account for interactions between the wind

73 and the plant for a range of plant species including maize. However, to date there is no

74 satisfactory description of the lodging process in maize that accounts for all the key

75 processes: plant/wind interaction, stem strength and anchorage strength.

76 The aim of this paper is to develop a realistic model of lodging in maize that can be used to

77 quantify the effects on lodging risk of agronomic lodging control approaches without relying

78 on the occurrence of natural lodging. This understanding will help farmers and crop advisors

79 develop agronomic strategies for minimising the lodging risk of future crops, for example by

80 optimising cultivar choice and seed rate. A second application of a lodging model is to help

81 farmers make in-season, or tactical, agronomic decisions to minimise lodging risk based on

82 observations of the growing crop. Examples of tactical decisions are changing the rate and

83 timing of nitrogen (N) fertiliser or the use of plant growth regulators to shorten the crop. The

84 lodging associated crop characteristics used as the lodging model inputs have not yet

85 developed when tactical decisions about remedial treatments must be made. Therefore, it will

86 be necessary to identify surrogate crop parameters that are reliable indicators of the values of

87 lodging associated plant characteristics. A previous study of oilseed rape (*Brassica napus* L.)

88 has demonstrated that the green area index of a crop at the start of stem extension is a useful

89 indicator of its future lodging risk (Berry and Spink, 2009). It is therefore possible that early

90 season canopy size may also be a useful indicator of future values of the lodging associated

91 plant characters in other crops such as maize.

92 The objectives of this paper are to: i) describe a model for stem and root lodging in maize, ii)

93 calibrate the anchorage strength component of the model, iii) evaluate the model's

94   applicability by assessing its ability to explain effects of crop husbandry on lodging risk and

95   iv) investigate the potential to further develop the lodging model to predict lodging risk at an

96   early enough growth stage for tactical agronomic action to minimise lodging risk.

97

2. Model of maize lodging

99   Aerodynamic investigations of the maize shoot have shown that it behaves as a damped

100   harmonic oscillator after being subjected to wind loading (Joseph et al., 2020). Therefore, the

101   mechanistic process of lodging in maize can be modelled in the same way as other plant

102   species with similar aerodynamic points of structural failure (e.g. wheat). A generalised

103   model used to describe the lodging process in cereals (Baker et al., 2014; Berry et al., 2003)

104   can therefore be adapted for maize, taking account of maize-specific calibrations estimated

105   by Joseph et al. (2020).   The maize lodging model assumes that the unit of lodging is a single

106   plant and stem lodging is expected if the wind-induced bending moment (leverage of the

107   shoot) exceeds the stem failure moment (stem strength at the point of failure), while root

108   lodging is expected if the leverage force exceeds the anchorage failure moment (anchorage

109   strength at the point of failure). It is assumed that stem failure results from buckling of the

110   stem, for which the mechanical properties of a cylinder apply. The mechanism of anchorage

111   failure in maize has been shown to be similar to wheat (Ennos et al. (1993). Therefore, failure

112   moment of the anchorage system is assumed to be proportional to the product of the spread of

113   the crown roots cubed and the shear strength of the surrounding soil, similar to anchorage

114   models for wheat (Baker et al., 1998), sunflower (Sporoso et al. 2008; 2010) and oats

115   (Mohammadi et al., 2020)

116   The bending moment (B) at any point along the shoot is obtained as a function of mean wind

117   speed $\overline{U}$, using the density of air ($\rho = 1.2$ kg/m^3), the drag area of the shoot ($A_{CF} = 0.153$ m^2),

118   the shoot's height at centre of gravity (X), the shoot's natural frequency (f_n), the acceleration

119   due to gravity ($g = 9.81$ m s^2), the turbulence intensity (I_u) and the shoot's damping ratio ($\theta =$

120   0.13). Values for A_{CF}, X, I_u and f_n were experimentally determined for maize by Joseph et al.

121   (2020).

122    $B = \frac{0.5\rho A C_F \bar{U}^2 \left(1+(2\pi f_n)^2(X/g)\right)}{(2\pi f_n)^2(X/g)} \left(\cos\left(\frac{\alpha l}{h}\right) - \cot\alpha \sin\left(\frac{\alpha l}{h}\right)\right) \left(1 + 6.86 I_u \left(1 + 0.366\left(\frac{\pi}{4\theta}\right)\right)^{0.5}\right)$

123   (1)

124   In the above equation, l and h represent the height above the ground at which the bending

125   moment is considered and the total height of the shoot respectively; α is a constant

126   determined from the relationship:

127    $(2\pi f_n)^2(X/g) = \frac{\alpha}{1-\cot\alpha}$ (2)

128   Stem lodging occurs when the shoot bending moment exceeds the shoot failure moment B_s

129   expressed as:

130    $B_s = \frac{\sigma\pi a^3}{4}\left(1 - \left(\frac{a-t}{a}\right)^4\right)$ (3)

131   Where σ is the yield stress at any point along the stem, a is the corresponding mean radius of

132   the stem and t is the mean stem wall thickness.

133   Similarly the moment acting on the root system (B_N) is specified in Baker et al. (2014) as,

134    $B_N = \frac{0.5\rho A C_F \bar{U}^2 \left(1+(2\pi f_n)^2(X/g)\right)}{(2\pi f_n)^2(X/g)} (1 + 3.44 I_u)\, N$ (4)

135   Where N is the number of shoots per plant.

136   Root lodging occurs when the wind-induced root bending moment exceeds anchorage failure

137   moment (B_R), which is calculated from the root plate spread (d), the shear strength of the

6

138 surrounding soil (s) and a constant (k_4) which is estimated by this study to have a value of 0.-

139 73 (Eq. 5).

$$B_R = sd^3k_4 \tag{5}$$

141 The mean wind speeds required to cause stem lodging ($\bar{U}_{LS}$) and root lodging ($\bar{U}_{LR}$) are

142 calculated by rearranging the bending moment expressions in Equations (1) and (4)

143 combining with Equations (3) and (5) respectively:

$$\bar{U}_{LS} = \left[\frac{\omega_n^2\left(\frac{X}{g}\right)n\left(\frac{\sigma\pi a^3}{4}\right)\left(1-\left(\frac{(a-t)}{a}\right)^4\right)}{\left(1+\omega_n^2\left(\frac{X}{g}\right)\right)(0.5\rho AC_F X)\left(\cos\left(\frac{\alpha l}{h}\right)-\cot\alpha\sin\left(\frac{\alpha l}{h}\right)\right)\left(1+6.86I_u\left(1+0.366\left(\frac{\pi}{4\theta}\right)\right)^{0.5}\right)}\right]^{0.5} \tag{6}$$

$$\bar{U}_{LR} = \left[\frac{\omega_n^2\left(\frac{X}{g}\right)\gamma Sd^3}{\left(1+\omega_n^2\left(\frac{X}{g}\right)\right)(0.5\rho A_{CF}X)(1+3.44I_u)}\right]^{0.5} \tag{7}$$

146

3. Field experimental methods

148 Field experiments involving different plant population and N rate treatments were set up to

149 produce maize crops with a range of lodging risks. Measurements on these field experiments

150 were carried out to provide data for calibrating the anchorage model, evaluating the general

151 plausibility of the lodging model, better understand how agronomic factors affect the risk of

152 stem and root lodging and to identify which early growing season plant characters may

153 predict lodging risk.

154 *3.1 Experiments*

155 Field experiments were set up in the UK in 2017 (UK17), UK in 2018 (UK18) and China in

156 2018 (CH18). The UK experiments were conducted at ADAS Gleadthorpe near Mansfield,

157 Nottinghamshire on a loamy sand over sandstone. The experimental design was a two-way

factorial with plant population density (4, 6, 12 plants/m^2) and rate of N fertiliser (0, 100 and

200 kg/ha N, with 50% at sowing and 50% at leaf 4) as the treatment factors, and each

treatment combination replicated three times. The plot size was 3m x 12m. The variety was

Dualto. The crops were planted in May and harvested for forage in September. The China

experiment was conducted in Lishu County (43530E), Jilin Province in Northeast China, on

Black soil (USDA Haploboroll). The experimental design was a split-plot with plant

population density (5.5, 7, 8.5 and 10 plants/m^2) as the treatment factor on the main plots and

rate of N fertiliser rate (0, 60, 120,180, 240 and 300 kg/ha N, with 33% at sowing and 67% at

leaf 8) as the treatment factor on the sub-plots, with each treatment combination replicated

three times. The plot size was 9m x 12m. A mid late maturing variety Liangyu 66 was used.

The crops were planted in May and harvested for grain in early October.

3.2 Measurements

3.2.1 Pre flowering plant characters

The green leaf area index (LAI) was measured when leaves 4, 6 and 8 were fully emerged

using a moving belt leaf area meter (Li-Cor Model 3100, Delta-T Devices, Burwell,

Cambridge, UK). Plant height, fresh weight and dry weight was measured on 16 plants

sampled from each plot.

3.2.2 Post-flowering plant characters

The field experiment was regularly inspected for any incidences of natural lodging between

flowering and harvest.

3.2.2.1 Shoot characteristics

Natural Frequency was measured in the field on ten plants per plot when cobs were at the

milky ripe stage. The plant was isolated from neighbouring plants and its shoot displaced by

0.20 m from the vertical and released. The time for three complete oscillations to occur in the

182 line of displacement was recorded. Natural frequency (Hz) was calculated as the number of

183 oscillations divided by the timed period (seconds) (Berry et al., 2000).

184 Plants were cut off at ground level and crop height was measured from the stem base to the

185 top of the inflorescence. The entire shoot was balanced on a pivot and its height at centre of

186 gravity was measured as the distance from the point of balance to the base of the stem (mm).

187 3.2.2.2 Stem characteristics

188 Each internode was numbered starting with internode 1 at the bottom of the plant. The length

189 (mm) of each internode was measured using a ruler and the diameter (mm) was measured at

190 the middle of each internode using digital callipers (Etalon, Switzerland). The breaking

191 strength (Newtons) of internodes 1-3 (combined), internode 5 and internode 8 were measured

192 using a three-point bending test with a digital Force Gauge (Mecmesin Ltd, Horsham, UK)

193 (Figure 1). Each internode was cut at its mid-point and two measurements of the stem wall

194 width were recorded at right angles to each other (Figure 1).

A   B   C
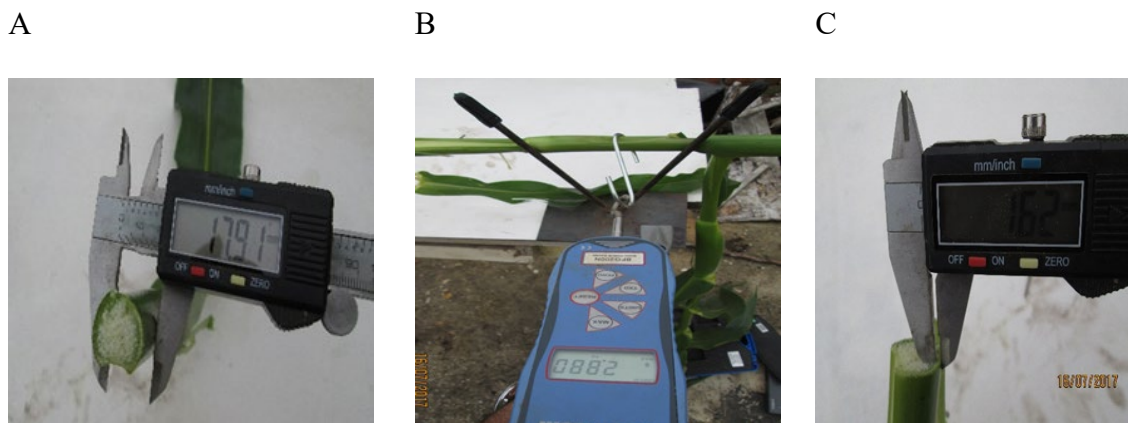
195 Figure 1. A) measurement of stem diameter, B) three-point breaking test used stem for stem

196 breaking strength determination, C) measurement of stem wall width

197 3.2.2.3 Root characteristics

198   Ten plants per plot were excavated to a soil depth of about 0.20 m taking care not to break off

199   the brace roots. The soil was carefully removed from the roots and the brace roots identified

200   as those that emerge above the soil surface and the crown roots as those that emerge from

201   below the soil surface (Figure 2). The number of brace roots and the number of crown roots

202   were counted on each plant. The maximum crown root plate spread at a soil depth of 80 mm

203   was measured along with the crown root plate spread at 90° to the maximum crown root

204   spread and the maximum depth of roots that were extracted (Figure 2). For the brace roots,

205   the maximum root plate spread at soil surface, the root plate spread at 90° to the maximum

206   root spread and the maximum height above the soil surface where they joined the stem was

207   recorded (Figure 2).

208   At the cob milky ripe stage, root anchorage strength was measured on a separate set of

209   experimental plots to the main experiment described above, with plant population densities of

210   4, 6 and 12 plants/m². These measurements were made using a Mecmesin force gauge by

211   applying a perpendicular force to the stem at 0.10 m from the ground (Fouere et al., 1995;

212   Shengqun et al., 2012). The maximum force (Newtons) to displace the stem by 45 degrees

213   from the vertical was recorded, together with the soil shear strength at 0.10 m soil depth using

214   a shear vane (Pilcon, Basingstoke, UK).
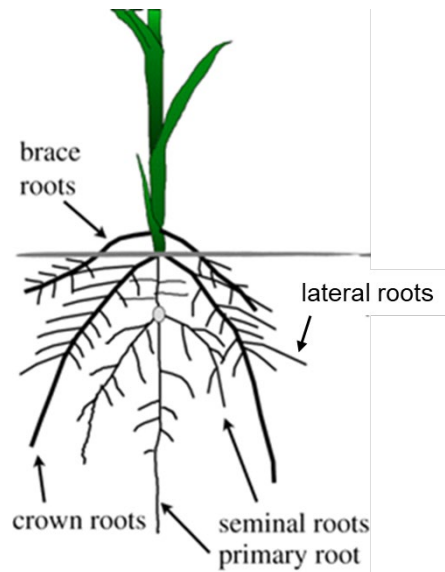
215

216   Figure 2 Root structure of maize

217

218

219   *3.3 Calculations*

220   The stem failure moment (B_S) was calculated from the measured tensile failure strength (F_S)

221   and length (L) of the internode, as described in Berry et al. (2000).

222     $$B_S = \frac{F_S L}{4}$$ (8)

223

224   Anchorage failure moment (B_R) was calculated according to equation 5.

225

226   *3.4 Statistical analysis*

227   Analysis of variance procedures for fully randomised two-way factorial and split-plot

228   experimental designs were used within Genstat 18 software to calculate standard errors of

229   differences between means (S.E.D.) and significant differences between treatments. Genstat

11

230   was also used to perform linear regression analysis and calculate correlation coefficients

231   between the measured plant characteristics.

232

233   **4. Results**

234   *4.1 Anchorage strength*

235   The anchorage strength tests showed that reducing plant population from 12 to 4 plants/m^2

236   significantly increased anchorage failure moment from 23.7 Nm to 45.5 Nm, average crown

237   root spread from 158 mm to 208 mm, crown root number per plant from 11.6 to 14.0, brace

238   root number from 0.6 to 10.2 per plant and root fresh weight from 180 g to 580 g ($P < 0.001$).

239   Linear regression analysis was carried out to test whether the anchorage failure moment was

240   linearly related to the product of the crown root plate spread and shear strength of the

241   surrounding soil, as has been found for cereal species. This showed a significant positive

242   relationship ($P < 0.01$; Figure 3) with a slope of 0.073 and intercept of 16.7 Nm. This

243   relationship was used to calibrate the lodging model's calculation of anchorage failure

244   moment (Equation 5). Multiplying the product of crown root plate spread cubed and soil

245   shear strength by crown root number increased the R^2 value by a modest amount from 0.54 to

246   0.60. Of the root parameters measured, root fresh weight had the strongest relationship with

247   the anchorage failure moment with an R^2 of 0.80.
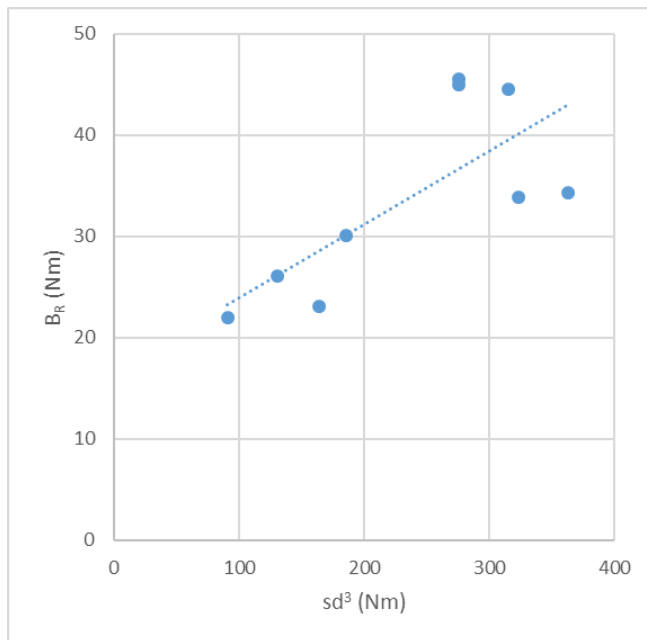
Figure 3. Relationship between measured anchorage failure moment (BR) and the product of crown root plate (d) cubed and soil strength (s), y=0.073x + 16.7; R^2=0.54; P < 0.01).

4.2 Crop husbandry effects on biomass yield and plant character associated with lodging

The effects of plant population and N fertiliser rate on the measurements of the plant characters associated with lodging are described in tables 1 to 6, with effects on the calculations of stem failure wind speed described in Tables 7 and 8). Increasing plant population from 4 to 12 plants/m^2 increased the biomass yield from 16.7 to 25.5 t/ha for the UK17 experiment and from 12.1 t/ha to 15.6 t/ha in the UK18 experiment (P < 0.001; Tables 1 and 2). Increasing N rate did not significantly (P > 0.05) increase biomass in the UK experiments. By contrast, in the CH18 experiment the plant population and N rate treatments interacted such that increasing plant population from 5.5 to 10 plants/m^2 increased biomass yield at low N rates only and had no effect when fertilised at 180 or 300 kg N/ha. Increasing N rate significantly (P < 0.05) increased biomass at all plant populations, except 10 plants/m^2 (Table 3).

263 Increasing the plant population significantly (P < 0.01) reduced the anchorage and stem

264 failure wind speeds in all experiments (Tables 7 and 8), thus indicating greater risk to root

265 and stem lodging. Increasing the plant population increased the risk of lodging because it

266 significantly reduced the spread of the root plate in all experiments and the depth of the root

267 plate in the UK17 and UK18 experiments (Table 1, 2 and 3). Increasing plant population also

268 increased the leverage exerted on the plant base by increasing plant height and height at

269 centre of gravity in the UK17 and CH18 experiments and reducing the plant's natural

270 frequency (rate of shoot oscillation) in all experiments (Table 1, 2 and 3). Increasing plant

271 population increased the risk of stem lodging by reducing stem strength as a result of

272 narrower stems in all experiments and additionally as a result of thinner walled stems in the

273 UK17 and UK18 experiments (Table 4, 5 and 6).

274 Increasing the rate of N fertiliser did not significantly affect the stem failure wind speeds in

275 any of the experiments (Tables 7 & 8). In the UK17 and UK18 experiments, this was because

276 changes in N rate did not significantly affect the plant characteristics that determine plant

277 leverage or stem strength. In the CH18 experiment, the effect of increasing plant height with

278 greater N on stem failure windspeed was counteracted by an increase in strength of

279 internodes 5 and 8 as N fertiliser rate was increased from 60 to 300 kg N/ha. However,

280 increasing N rate did reduce the root failure wind speed in CH18 (P < 0.01; Table 8),

281 primarily as a result of its effect to increase leverage.

282 Table 1. UK17: Biomass yield and character associated with plant leverage and anchorage

283 strength

Plants/m^2	N applied kg/ha	Biomass yield at harvest (t/ha)	Plant height (cm)	Height at centre of gravity (cm)	Natural Frequency (Hz)	Root plate spread (cm)	Root plate depth (cm)
4	0	17.6	246	85.7	1.22	16.0	10.74
4	100	16.2	241	85.4	1.16	16.2	10.32

Plants/m²	N rate kg/ha	Biomass yield	Plant height	Height to CoG	Natural Frequency	Root plate spread	Root plate depth
4	200	16.3	241	86.5	1.15	17.3	10.72
6	0	20.5	257	93.1	1.07	16.1	11.03
6	100	20.2	256	93.6	0.97	15.3	9.77
6	200	19.8	258	93.2	0.99	15.2	9.89
12	0	25.7	285	109.2	0.81	12.1	8.91
12	100	26.4	280	106.5	0.72	13.1	8.82
12	200	24.4	276	108.9	0.76	13.0	8.85
4	mean	16.7	243	85.9	1.177	16.5	10.59
6	mean	20.2	257	93.3	1.010	15.5	10.23
12	mean	25.5	280	108.2	0.763	12.7	8.86
mean	0	21.2	263	96.0	1.033	14.7	10.23
mean	100	20.9	259	95.2	0.950	14.9	9.64
mean	200	20.2	258	96.2	0.967	15.2	9.82
Plants/m²	SED	0.540***	2.7***	0.58***	0.038***	0.47***	0.890**
Nitrogen	SED	0.540	2.7	0.58	0.038	0.47	0.890
Interaction	SED	0.936	4.6	1.01	0.138	0.82	1.541

***<0.001 **<0.01 * <0.05

Table 2. UK18: Biomass yield and character associated with plant leverage and anchorage strength.

Plants/m²	N rate kg/ha	Biomass yield at harvest (t/ha)	Plant height (cm)	Height to centre of gravity (cm)	Natural Frequency (Hz)	Root plate spread (cm)	Root plate depth (cm)
4	0	13.7	206	74.5	1.19	20.8	8.80
4	100	10.6	197	69.3	1.08	21.9	9.29
4	200	11.9	202	73.4	1.11	20.4	8.75
6	0	12.1	197	71.2	1.19	20.0	8.59
6	100	12.5	205	76.2	1.14	20.7	8.06
6	200	14.1	201	76.2	1.03	18.4	8.33
12	0	15.8	212	81.4	1.04	16.6	7.24
12	100	14.8	195	70.2	1.03	13.7	6.88
12	200	16.2	198	72.8	0.99	15.8	7.08
4	mean	12.1	202	72.4	1.13	21.1	8.95
6	mean	12.9	201	74.5	1.12	19.7	8.33
12	mean	15.6	202	74.8	1.02	15.3	7.07
mean	0	13.9	205	75.7	1.14	19.1	8.21
mean	100	12.6	199	71.9	1.08	18.8	8.08
mean	200	14.1	200	74.1	1.04	18.2	8.05
Plants/m²	SED	1.568**	6.06	2.426	0.0357*	1.009***	0.441**
Nitrogen	SED	1.568	6.06	2.426	0.0357	1.009	0.441
Interaction	SED	2.716	10.5	4.202	0.0618	1.748	0.736

Table 3. CH18: Biomass yield and characters associated with plant leverage and anchorage strength

Plants/m^2	N rate kg/ha	Biomass at harvest (t/ha)	Total plant height (cm)	Height to centre of gravity (cm)	Natural Frequency (Hz)	Root plate spread (cm)	Root plate depth (cm)
5.5	60	17.0	232	87.5	0.882	14.9	10.47
5.5	180	21.5	261	98.1	0.831	16.2	10.82
5.5	300	23.8	270	103.7	0.823	17.4	11.03
7	60	15.2	231	87.9	0.868	13.9	10.50
7	180	24.5	259	101.2	0.815	15.1	8.93
7	300	25.5	271	106.1	0.749	16.1	9.77
8.5	60	16.4	226	85.7	0.806	14.7	9.73
8.5	180	26.9	264	103.5	0.775	14.7	9.32
8.5	300	25.2	268	107.2	0.757	15.3	9.56
10	60	23.1	244	93.6	0.759	14.0	9.14
10	180	23.0	263	103.2	0.773	13.2	9.37
10	300	25.6	267	105.8	0.719	14.5	10.62
5.5	mean	20.8	254	96.4	0.845	16.1	10.77
7	mean	21.7	254	98.4	0.811	15.0	9.73
8.5	mean	22.8	253	98.8	0.779	14.9	9.54
10	mean	23.9	258	100.9	0.750	13.9	9.71
mean	60	17.9	234	88.7	0.829	14.4	9.96
mean	180	24.0	262	101.5	0.799	14.8	9.61
mean	300	25.0	269	105.7	0.762	15.8	10.24
Plants/m^2	SED	1.67	3.9	1.12*	0.016**	0.49*	0.88
Nitrogen	SED	1.02***	3.2***	1.49***	0.015***	0.33**	0.42
Interaction	SED	2.36*	6.5	2.69	0.029	0.72	1.11

Table 4. UK17: Length, diameter, wall width and failure moment for the bottom three internodes (I/N 1-3), internode 2 (I/N 2), internode 5 (I/N 5) and internode 8 (I/N 8).

Plants/m2	N rate kg/ha	Internode Length (cm)			Internode Diameter (mm)			Wall width (mm)			Stem Failure moment (Nm)		
		I/N 1-3	I/N 5	I/N 8	I/N 2	I/N 5	I/N 8	I/N 2	I/N 5	I/N 8	I/N 1-3	I/N 5	I/N 8
4	0	31.8	21.8	22.5	27.1	21.8	18.3	3.23	1.34	0.759	19.0	7.75	4.74
4	100	39.4	21.3	22.0	27.4	20.7	18.3	3.02	1.47	0.713	19.1	7.44	4.69
4	200	32.5	21.6	21.2	26.8	21.1	17.6	2.71	1.24	0.691	16.9	7.10	4.19
6	0	37.4	24.0	22.7	25.4	19.6	17.0	2.83	1.40	0.699	18.3	6.54	3.53
6	100	34.1	23.5	22.2	25.8	20.9	18.0	2.84	1.34	0.790	16.7	7.06	3.80
6	200	33.8	23.4	22.9	25.7	20.7	17.9	2.68	1.32	0.728	17.5	7.25	3.53
12	0	48.8	25.9	22.4	21.0	18.7	14.7	1.92	1.05	0.777	11.5	4.42	2.35
12	100	49.1	26.2	22.3	21.2	18.3	14.7	1.89	1.08	0.710	12.7	4.39	2.34
12	200	44.7	26.0	22.4	21.4	18.6	15.2	1.94	0.90	0.650	11.5	4.36	2.84
4	mean	34.6	21.6	21.9	27.1	21.2	18.1	2.99	1.35	0.721	18.3	7.43	4.54
6	mean	35.1	23.6	22.6	25.6	20.4	17.6	2.78	1.35	0.739	17.5	6.95	3.62
12	mean	47.5	26.0	22.4	21.2	18.5	14.9	1.92	1.01	0.712	11.9	4.39	2.51
mean	0	39.3	23.9	22.5	24.5	20.0	16.7	2.66	1.26	0.745	16.2	6.24	3.54
mean	100	40.9	23.7	22.2	24.8	20.0	17.0	2.58	1.30	0.738	16.2	6.30	3.61
mean	200	37.0	23.7	22.2	24.6	20.1	16.9	2.44	1.15	0.690	15.3	6.24	3.52
Plants/m2	SED	2.64***	0.49***	0.64	0.30***	0.40***	0.23***	0.166***	0.056	0.074***	1.43***	0.243***	0.224***
Nitrogen	SED	2.64	0.49	0.64	0.30	0.4	0.23	0.166	0.056	0.074	1.43	0.243	0.224
Interaction	SED	4.58	0.849	1.11	0.52	0.70	0.40	0.269	0.098	0.123	2.48	0.422	0.389

Table 5. UK18: Length, diameter, wall width and failure moment for the bottom three internodes (I/N 1-3), internode 2 (I/N 2), internode 5 (I/N 5) and internode 8 (I/N 8).

Plants/m²	N rate kg/ha	Internode Length (cm)			Internode Diameter (mm)			Wall width (mm)			Stem Failure moment (Nm)		
		I/N 1-3	I/N 5	I/N 8	I/N 2	I/N 5	I/N 8	I/N 2	I/N 5	I/N 8	I/N 1-3	I/N 5	I/N 8
4	0	29.8	15.5	13.8	24.7	21.0	12.96	1.095	0.781	0.498	10.55	4.52	1.96
4	100	26.8	14.6	13.0	23.6	18.5	12.88	1.049	0.738	0.482	8.46	3.74	2.06
4	200	30.6	15.0	13.8	23.3	18.3	11.84	0.912	0.775	0.480	9.74	3.96	1.81
6	0	28.5	14.6	20.2	22.0	17.3	11.86	0.875	0.750	0.498	8.26	3.40	1.51
6	100	29.1	16.4	13.1	22.2	18.2	11.91	0.941	0.702	0.443	7.84	3.54	1.53
6	200	27.3	17.0	13.1	21.0	18.3	11.62	0.837	0.671	0.431	7.42	2.04	1.30
12	0	33.4	18.2	13.4	19.4	16.3	10.40	0.816	0.537	0.415	6.92	3.97	1.10
12	100	31.8	15.3	12.6	19.5	15.1	9.89	0.776	0.500	0.375	5.99	3.13	0.89
12	200	29.4	16.7	12.8	19.5	15.1	10.05	0.699	0.540	0.354	5.71	2.16	0.85
4	mean	29.1	15.0	13.5	23.9	19.2	12.56	1.019	0.765	0.487	9.58	4.07	1.94
6	mean	28.3	16.0	15.5	21.8	17.9	11.80	0.884	0.708	0.457	7.84	2.99	1.45
12	mean	31.5	16.7	12.9	19.5	15.5	10.11	0.764	0.526	0.381	6.21	3.09	0.95
mean	0	30.6	16.1	15.8	22.0	18.2	11.74	0.929	0.689	0.470	8.58	3.96	1.52
mean	100	29.2	15.4	12.9	21.8	17.3	11.56	0.922	0.647	0.433	7.43	3.47	1.49
mean	200	29.1	16.2	13.2	21.3	17.2	11.17	0.816	0.662	0.422	7.62	2.72	1.32
Plants/m²	SED	1.31	0.80	1.86	0.62***	0.81***	0.335***	0.0463***	0.0384**	0.236	0.656***	0.243***	0.103***
Nitrogen	SED	1.31	0.80	1.86	0.62	0.81	0.335	0.0463*	0.0384	0.427	0.656	0.243	0.103
Interaction	SED	2.27	1.39	3.22	1.08	1.41	0.580	0.0801	0.0665	0.441	1.136	0.421	0.178

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Table 6. CH18: Length, diameter, wall width and failure moment for the bottom three internodes (I/N 1-3), internode 2 (I/N 2), internode 5 (I/N 5) and internode 8 (I/N 8).

Plants/m²	N rate kg/ha	Internode Length (cm)			Internode Diameter (mm)			Wall width (mm)			Stem Failure moment (Nm)		
		I/N 1-3	I/N 5	I/N 8	I/N 2	I/N 5	I/N 8	I/N 2	I/N 5	I/N 8	I/N 1-3	I/N 5	I/N 8
5.5	60	24.2	16.4	13.5	22.4	21.0	19.5	1.38	1.53	1.02	21.4	9.49	4.47
5.5	180	23.9	19.0	15.2	23.1	22.1	21.5	1.64	1.53	1.08	23.8	12.47	5.45
5.5	300	26.1	19.6	14.8	25.1	23.6	22.9	1.74	1.53	1.36	27.4	14.09	7.42
7	60	24.2	16.7	14.0	20.6	19.2	20.1	1.46	1.35	1.10	23.2	8.42	4.25
7	180	26.3	19.3	15.7	22.7	21.6	23.4	1.73	1.51	1.27	25.0	11.51	6.13
7	300	28.3	19.2	16.7	24.2	21.7	19.7	1.55	1.59	1.27	27.1	10.84	6.40
8.5	60	23.9	16.2	13.5	20.3	19.5	18.8	1.45	1.44	1.11	22.0	7.51	3.59
8.5	180	30.6	19.3	15.0	22.1	20.6	21.8	1.60	1.42	1.14	26.0	9.16	4.76
8.5	300	29.0	19.8	17.2	23.2	22.3	20.9	1.56	1.63	1.37	23.9	8.74	4.87
10	60	26.8	18.3	13.7	19.0	18.2	19.5	1.23	1.31	1.07	20.7	8.03	4.12
10	180	29.0	19.0	15.9	20.3	19.6	19.8	1.56	1.33	1.25	20.2	7.25	4.24
10	300	28.0	17.7	17.0	21.3	20.6	18.6	1.42	1.39	1.24	19.4	7.04	4.31
5.5	mean	24.7	18.3	14.5	23.5	22.2	21.3	1.59	1.53	1.15	24.2	12.02	5.78
7	mean	26.3	18.4	15.5	22.5	20.8	21.1	1.58	1.48	1.22	25.1	10.26	5.59
8.5	mean	27.8	18.5	15.2	21.9	20.8	20.5	1.54	1.50	1.21	24.0	8.47	4.41
10	mean	28.0	18.3	15.5	20.2	19.5	19.3	1.40	1.34	1.19	20.1	7.44	4.22
mean	60	24.8	16.9	13.7	20.6	19.5	19.5	1.38	1.41	1.08	21.9	8.37	4.11
mean	180	27.4	19.2	15.5	22.1	21.0	21.6	1.63	1.45	1.19	23.7	10.10	5.14
mean	300	27.8	19.1	16.4	23.5	22.0	20.5	1.57	1.53	1.31	24.5	10.18	5.75
Plants/m²	SED	1.47	0.76	0.60	0.52**	0.49**	1.34	0.147	0.098	0.074	1.48	1.173*	0.541**
Nitrogen	SED	0.92**	0.34***	0.39***	0.31***	0.37***	0.63*	0.052***	0.062	0.051**	1.53	0.556**	0.347***
Interaction	SED	2.10	0.94*	0.87	0.73	0.77	1.69	0.170	0.140	0.111	2.90	1.483	0.783

Table 7. UK17 and UK18: Stem and anchorage failure wind speeds for the bottom three internodes (I/N 1-3), internode 2 (I/N 2), internode 5 (I/N 5) and internode 8 (I/N 8).

Plants/m²	N applied kg/ha	UK17				UK18			
		Anchorage (m/s)	I/N 1-3 (m/s)	I/N 5 (m/s)	I/N 8 (m/s)	Anchorage (m/s)	I/N 1-3 (m/s)	I/N 5 (m/s)	I/N 8 (m/s)
4	0	8.52	11.85	8.68	8.47	8.95	9.44	6.74	4.63
4	100	8.40	11.84	8.47	8.80	9.35	8.43	6.10	4.65
4	200	8.62	11.06	8.21	8.12	9.13	8.95	6.22	4.33
6	0	8.08	11.10	7.48	6.96	8.93	8.37	5.77	4.25
6	100	7.63	10.29	7.62	7.08	8.76	7.93	5.81	3.94
6	200	7.64	10.66	7.73	6.83	8.33	7.55	5.37	3.71
12	0	6.54	7.80	5.33	4.72	8.04	7.07	4.91	3.43
12	100	6.50	8.05	5.24	4.64	8.36	7.07	4.56	3.24
12	200	6.50	7.76	5.23	5.19	8.21	7.00	4.57	3.14
4	mean	8.51	11.58	8.45	8.46	9.14	8.94	6.35	4.54
6	mean	7.79	10.68	7.61	6.96	8.68	7.95	5.65	3.97
12	mean	6.51	7.87	5.27	4.85	8.21	7.05	4.68	3.27
mean	0	7.71	10.25	7.16	6.72	8.64	8.29	5.81	4.10
mean	100	7.51	10.06	7.11	6.84	8.82	7.81	5.49	3.94
mean	200	7.59	9.83	7.06	6.71	8.56	7.83	5.39	3.73
Plants/m²	SED	0.095***	0.482***	0.157***	0.229***	0.180 ***	0.297***	0.186***	0.172***
Nitrogen	SED	0.095	0.482	0.157	0.229	0.180	0.297	0.186	0.172
Interaction	SED	0.165	0.835	0.271	0.397	0.312	0.514	0.323	0.298

***<0.001 **<0.01 * <0.05

Table 8. CH18: Stem and Anchorage failure wind speeds

Plants/m^2	N rate kg/ha	Anchorage (m/s)	I/N 1-3 (m/s)	I/N 5 (m/s)	I/N 8 (m/s)
5.5	60	7.58	11.62	8.87	6.30
5.5	180	7.28	11.55	9.49	6.58
5.5	300	7.25	12.13	9.79	7.52
7	60	7.45	12.06	8.33	6.18
7	180	7.06	11.66	8.63	6.96
7	300	6.87	11.69	7.89	6.80
8.5	60	7.44	11.79	7.31	5.68
8.5	180	6.87	11.67	7.46	6.08
8.5	300	6.78	10.97	7.12	5.99
10	60	7.02	10.70	7.20	5.76
10	180	6.75	10.19	6.59	5.67
10	300	6.65	9.75	6.29	5.50
5.5	mean	7.37	11.8	9.38	6.80
7	mean	7.13	11.8	8.29	6.64
8.5	mean	7.03	11.5	7.29	5.92
10	mean	6.81	10.2	6.69	5.64
mean	60	7.37	11.5	7.93	5.98
mean	180	6.99	11.3	8.04	6.32
mean	300	6.89	11.1	7.77	6.45
Plants/m^2	SED	0.089**	0.382*	0.487**	0.362
Nitrogen	SED	0.048***	0.374	0.245	0.207
Interaction	SED	0.119	0.721	0.631	0.495

4.3 Predicting lodging associated lodging characters

Increasing the plant population increased the leaf area index (LAI) at the four, six and eight leaf stages in both the UK17 and UK18 field experiments and at the six and eight leaf stages in the CH18 experiment (P < 0.001; Tables 9 and 10). Increasing fertiliser rate from 60 to 180 kg N/ha caused a modest, but significant (P<0.05), increase in LAI of 0.34 units at Leaf 8 in the CH18 experiment, but there was no evidence that increasing the N fertiliser rate affected LAI between the four and eight leaf stages in the UK experiments.

In all experiments LAI measured at the four, six or eight leaf stage was positively correlated with biomass yield at harvest, the combined lengths of the bottom three internodes and the plant's natural frequency, negatively correlated with stem diameter, stem failure moment,

root plate dimensions measured after flowering and the calculated stem and root failure wind

speeds ($P < 0.05$; Table 11). The correlations were generally stronger in the UK17

experiment, for which there was also a positive correlation between LAI and crop height at

flowering and the length of the lower internodes.

Table 9. Leaf area index measured at 4, 6 and 8 leaf stages in the UK17 and UK18
experiments.

Plants/m2	N applied kg/ha	UK17			UK18		
		Leaf 4	Leaf 6	Leaf 8	Leaf 4	Leaf 6	Leaf 8
4	0	0.100	1.03	1.38	0.0243	0.553	2.29
4	100	0.100	0.87	1.23	0.0242	0.637	2.67
4	200	0.103	0.85	1.28	0.0243	0.634	1.77
6	0	0.158	1.51	1.81	0.0554	1.121	2.63
6	100	0.149	1.36	1.89	0.0554	0.829	2.82
6	200	0.170	1.44	1.72	0.0549	1.043	2.97
12	0	0.319	2.71	3.46	0.2206	1.686	3.74
12	100	0.302	2.71	3.54	0.2387	1.519	4.53
12	200	0.329	2.68	3.03	0.1982	1.551	4.30
4	mean	0.101	0.92	1.30	0.0243	0.608	2.24
6	mean	0.159	1.44	1.81	0.0552	0.998	2.81
12	mean	0.317	2.70	3.34	0.2192	1.585	4.19
mean	0	0.192	1.75	2.22	0.1001	1.120	2.89
mean	100	0.184	1.65	2.22	0.1061	0.995	3.34
mean	200	0.201	1.66	2.01	0.0925	1.076	3.01
Plants/m^2	SED	0.0071***	0.091***	0.217***	0.00774***	0.0592***	0.237***
Nitrogen	SED	0.0071	0.091	0.217	0.00774	0.0592	0.237
Interaction	SED	0.0123	0.157	0.375	0.01341	0.1026	0.410

***<0.001 **<0.01 * <0.05

Table 10. Leaf area index measured at 6 and 8 leaf stages in the CH18 experiment.

Plants/m2	N applied kg/ha	Leaf 6	Leaf 8
5.5	60	0.198	0.939
5.5	180	0.282	1.065
5.5	300	0.313	1.135
7	60	0.277	1.191
7	180	0.397	1.470
7	300	0.426	1.568

8.5	60	0.363	1.379
8.5	180	0.487	1.914
8.5	300	0.574	1.905
10	60	0.410	1.550
10	180	0.524	1.962
10	300	0.645	2.179
5.5	mean	0.264	1.05
7	mean	0.367	1.41
8.5	mean	0.475	1.73
10	mean	0.526	1.90
mean	60	0.312	1.26
mean	180	0.423	1.60
mean	300	0.490	1.70
Plants/m^2	SED	0.0359 ***	0.0814 ***
Nitrogen	SED	0.0101 ***	0.0721 ***
Interaction	SED	0.0395 **	0.1432

313   ***<0.001 **<0.01 * <0.05

314

315   Table 11. Correlation coefficients calculated for leaf area index measured at leaf (L) 4, 6 & 8

316   with plant characteristics associated with lodging and biomass yield. White cells represent

317   strong positive correlations and dark grey cells represent strong negative correlations.

	UK17			UK18			CH18	
	L4	L6	L8	L4	L6	L8	L6	L8
Biomass yield	0.90	0.92	0.84	0.54	0.44	0.48	0.70	0.66
Crop height	0.91	0.95	0.87	0.03	0.01	-0.04	0.57	0.50
Height at centre of gravity	0.97	0.96	0.91	0.11	0.11	0.01	0.70	0.64
Natural Frequency	-0.87	-0.85	-0.80	-0.46	-0.38	-0.38	-0.90	-0.87
Length internodes 1-3	0.69	0.74	0.70	0.40	0.30	0.24	0.80	0.85
Length Internode 5	0.88	0.91	0.74	0.22	0.25	0.11	0.40	0.35
Length internode 8	0.19	0.30	0.21	-0.15	-0.05	-0.13	0.75	0.67
Diameter internode 2	-0.96	-0.96	-0.88	-0.73	-0.76	-0.64	-0.15	-0.25
Diameter Internode 5	-0.74	-0.74	-0.71	-0.63	-0.62	-0.63	-0.07	-0.19
Diameter internode 8	-0.93	-0.90	-0.88	-0.69	-0.67	-0.59	-0.19	-0.23
Wall width internode 2	-0.77	-0.75	-0.72	-0.62	-0.70	-0.57	-0.02	-0.08
Wall width Internode 5	-0.20	-0.19	-0.22	-0.76	-0.71	-0.55	-0.13	-0.24
Wall width internode 8	-0.12	-0.05	0.07	-0.25	-0.31	-0.09	0.55	0.45
Failure moment internodes 1-3	-0.77	-0.69	-0.67	-0.60	-0.59	-0.59	-0.24	-0.27
Failure moment Internode 5	-0.93	-0.88	-0.81	-0.66	-0.63	-0.65	-0.49	-0.57
Failure moment internode 8	-0.85	-0.84	-0.78	-0.70	-0.70	-0.66	-0.18	-0.27
Root plate spread	-0.84	-0.86	-0.78	-0.76	-0.70	-0.72	-0.28	-0.41
Root plate depth	-0.68	-0.64	-0.72	-0.71	-0.64	-0.66	-0.39	-0.47
Failure wind speed internode 2	-0.89	-0.83	-0.80	-0.74	-0.73	-0.68	-0.75	-0.74

Failure wind speed Internode 5	-0.97	-0.94	-0.87	-0.81	-0.77	-0.77	-0.81	-0.86
Failure wind speed internode 8	-0.93	-0.92	-0.86	-0.76	-0.73	-0.69	-0.49	-0.56
Failure wind speed anchorage	-0.87	-0.86	-0.83	-0.65	-0.62	-0.65	-0.59	-0.70

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319

5. Discussion

321 The model of the process of maize lodging has been evaluated in UK and China

322 environments. The lodging model described in this paper calculates failure wind speeds of

323 lower internodes 2 and 5 of between 5 and 12 m/s, failure wind speeds of internode 8 of 3 to

324 7 m/s and root failure wind speeds for soil at field capacity water content of 6 to 9 m/s. These

325 calculated failure wind speeds represent average wind velocities at crop height. The gust

326 values at crop height that are likely to cause lodging will be 2–2.5 times greater than these

327 values. The failure wind speed values can also be extrapolated to the normal meteorological

328 measurement height of 10 m above ground level through the use of the logarithmic velocity

329 profile using the method described by Joseph et al. (2020) From this a failure wind speed of 4

330 m/s extrapolates to a velocity at 10 m height of approximately 12 m/s. For context, in the UK,

331 the 99th percentile average hourly wind speed at 10 m height is between 11 and 13 m/s

332 (Cook, 1985). Therefore, the failure wind speeds calculated for the maize crops grown in the

333 field trials would only be expected to be exceeded a small proportion of the time. None of the

334 field trials described in the study experienced natural lodging which indicates that the

335 calculated failure wind speeds are realistic for the test crops in question.

336 The root failure wind speeds when the soil is at field capacity are less than, or greater than,

337 the failure wind speed of the lower internode 2, depending on the experiment. This implies

338 that stem or root lodging may be most prevalent depending on the characteristics of the plant

339 and the conditions it experiences. This is consistent with detailed observations of maize

340 lodging which have shown both stem and root lodging to be possible (Hu et al., 2013; Fincher

et al. 1985; Kamara et al. 2003). The calculated stem failure wind speeds are greatest for the lower internode 2 and decline by more than half for the middle internode 8. This is because the strength of internode 8 was measured to be less than one quarter of the strength of internode 2, but the force that internode 8 must support was calculated to be more than one quarter of the force that internode 2 must support. At this point it should be recognised that towards the top of the plant, the stem will be more flexible, and will be the part of the crop that behaves least like the bending cantilever assumed in the lodging model. We would therefore expect the model to predict lower stem failure wind speeds with greater reality than for upper parts of the stem and possibly also the mid stem. Further research is required to test this part of the model. For the lower internodes, for which the model assumptions are most applicable, the model predicts that failure at internode 5 is more likely than failure of internode 2 in all the experiments. Observations of natural lodging have shown that stem failure can be at any point between the soil and the cob (Arnold and Josephson, 1975) and can therefore occur on the bottom or middle internodes.

The maize lodging model calculated that increasing plant population substantially reduced the stem and root failure wind speeds, thus increasing the likelihood of lodging. Increasing plant density from what may be regarded commercially as low (6 plants/m^2) to high (10-12 plants/m^2) plant densities was estimated to reduce the stem and root failure wind speeds by 1-3 m/s. Joseph et al. (2020) estimated that a reduction of 2 m/s results in the risk of a critical wind speed being exceeded increasing by an order of magnitude, and a change of 4 m/s results in a two order of magnitude change in risk. These predictions for increased plant density to cause a substantial increase in lodging risk are consistent with observations of plant population effects on natural lodging (Guo et al., 2019; Sher et al., 2017; Jun et al., 2017). Previous studies have shown that increasing N fertiliser either has little effect on lodging risk or increases resistance to stem lodging by increasing stem diameter (Peng et al. 2014; Shi et

366   al., 2016). These findings are also consistent with the prediction of the effect of N fertiliser

367   on lodging made by the maize lodging model described in this present study.

368   Investigation of maize anchorage by this study demonstrated that the spread of the root plate

369   is a key determinant of anchorage strength similar to that used in a model of wheat lodging

370   by Berry et al. (2003). This is consistent with Ennos et al. (1993) who concluded that the

371   mechanism of anchorage failure in maize was similar to wheat. The angle of root spread has

372   also been shown to be a key criterion for determining varietal differences in maize anchorage

373   strength (Liu et al., 2012). Other root characteristics have been shown to be superior

374   predictors of anchorage strength in maize including the biomass of the roots in the upper

375   region of soil by this present study and the number and thickness of crown roots (Liu et al.,

376   2012). However, it should be recognised that these rooting characteristics require much more

377   time to measure than the spread of the root plate, which limits their utility as a screening

378   method for anchorage strength.

379   A sensitivity analysis of the key traits that determine the wind induced shoot leverage (natural

380   frequency), anchorage strength (root plate spread) and stem strength itself showed that stem

381   failure wind speed was influenced more by variation in stem strength than by variation in

382   shoot natural frequency and root failure wind speed was influenced more by variation in the

383   spread of the root plate than by variation in shoot natural frequency (Figure 4). Therefore

384   plant breeders should focus on increasing stem strength and anchorage strength to achieve the

385   greatest increase in lodging resistance. Measuring stem strength and shoot natural frequency

386   are quite laborious, so it will be useful to identify surrogate measures that provide a

387   reasonable approximation of these traits, particularly for stem strength. Stem diameter and

388   stem strength were generally closely related (R=0.55 to 0.86). Crop height was also generally

389   well correlated with natural frequency (R= -0.50 to -0.87). Both stem diameter and crop

390   height are simple traits to measure which increases their utility as a screening tool. Root plate

391   spread, the key component of root failure wind speed, is less easy to measure because the

392   plant must be excavated, however it may be possible to develop a procedure to assess this

393   trait without washing the soil from the roots which would reduce the measurement time

394   substantially. Further research is required to assess whether a simplified lodging model can

395   be developed which uses the key 'easy-to-measure' traits (crop height, stem diameter and

396   root plate spread) and provides a sufficiently reliable estimate of lodging risk. The correlation

397   analysis also reveals that the maize biomass yield was negatively correlated with lodging

398   resistance (stem and root failure wind speed) (R = -0.24 to -0.88). This illustrates the

399   important trade-off that maize growers and advisors must consider when choosing the

400   optimum combination of agronomic treatments.

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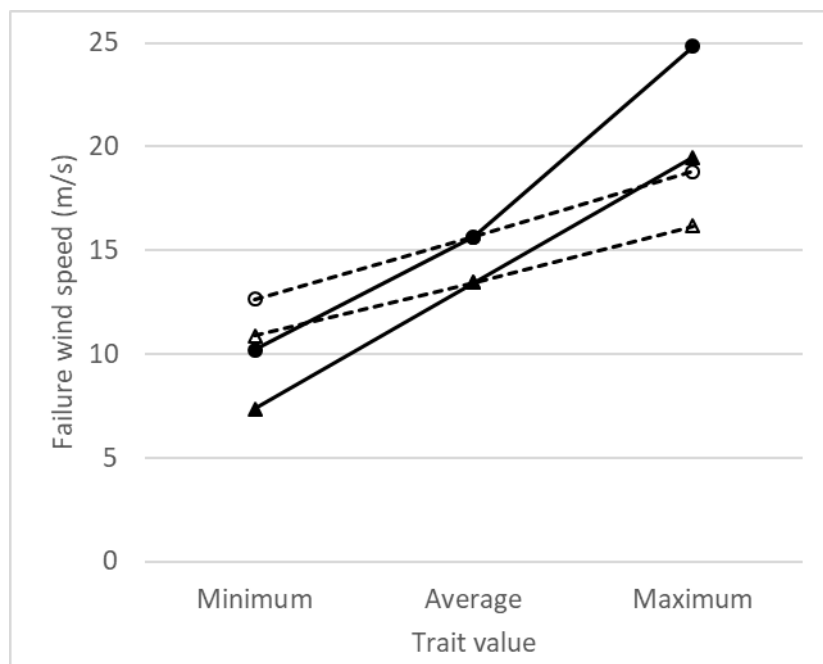
402

403   Figure 4. Sensitivity analysis for a selection of the model inputs. Minimum and maximum

404   values represent the maximum range of treatment values observed across all experiments in

405   this study. Effect of trait changes on stem failure wind speed: natural frequency (open

406   triangles, dashed line), stem strength (closed triangles dashed line). Effect of trait changes on

407   root failure wind speed: natural frequency (open circles, solid line), stem strength (closed

408   circles, solid line).

409   This study has demonstrated that the LAI measured at leaf 4, 6 or 8 is a good indicator of a

410   crop's risk of lodging later in the growing season. This relationship is mainly caused by

411   variation in plant population which has a strong effect on both early LAI and the lodging

412   associated plant characters that have a strong influence on the calculation of stem and root

413   failure wind speed such as stem strength and root plate spread. Regression analysis of the

414   LAI measured at leaf 6 and the failure wind speed of internode 5 showed that the best model

415   fit was parallel lines with different Y intercepts (P < 0.001, R^2 = 0.86; Figure 5). An increase

416   in the LAI measured at leaf 6 of one unit corresponded to a reduction in the failure wind

417   speed of internode 5 of approximately 2 m/s (Figure 5). In 2018, the crop experienced water

418   stress at Leaf 6 which may explain why the relationship in this experiment was different to

419   the other experiments. This analysis indicates that early measurements of canopy size could

420   be used to predict the risk of lodging in time for the application of remedial treatments such

421   as plant growth regulators that have been shown to reduce lodging risk by reducing the rate of

422   stem extension and final crop height (Shekoofa and Emam, 2008; Spitzer et al., 2015). Plant

423   growth regulators are effective when applied at the 8-9 leaf stage and later at the 4-6

424   detectable node stage (Spitzer et al., 2015), therefore predicting lodging risk at the 4 to 8 leaf

425   stage will be early enough to make decisions about whether to apply this treatment. The

426   similar sensitivity between experiments of the failure wind speed to changes in early LAI

427   suggests that early LAI could be used to quantify intra-field variation in lodging risk. This

428   could form the basis for spatially varying the rates of remedial treatments according to

429   variation in lodging risk. However, the different Y intercepts between the experiments means

430   further research is required to develop a quantitative prediction between fields. Additional

431   information such as variety maybe required to achieve this. Leaf area index is laborious to

432   measure, but the use of spectral indices recorded by remote sensing devices should provide

433   an efficient alternative for measuring LAI repeatedly over large spatial extents (Xia et al.,

434   2016). The concept of spatially of varying plant growth regulator applications within fields

435   based on remotely sensed information about canopy size has been demonstrated in wheat by

436   (Griffin and Hollis, 2017).
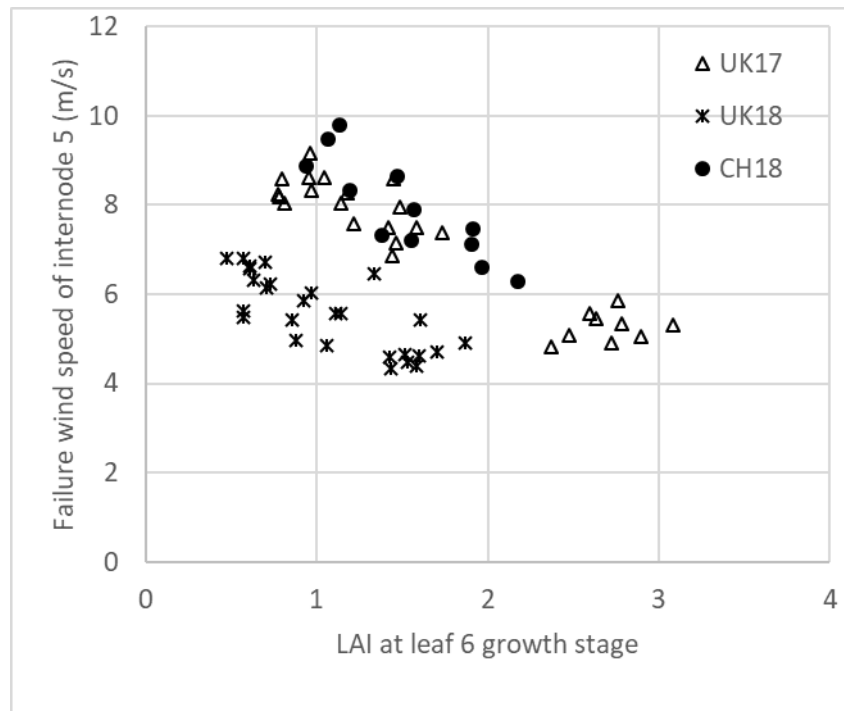
437

438   Figure 5. Relationship between the failure wind speed of internode 5 at tasselling and the LAI

439   measured at when leaf 6 had fully expanded.

440   After further validation the maize lodging model described in this paper could form the basis

441   of a decision support system that helps farmers and crop advisors to strategically plan crop

442   management systems that maximises productivity and minimises lodging risk. Predictions of

443   lodging risk based on the status of the developing crop, using measures such as LAI, will help

444   farmers to tactically fine-tune crop husbandry and take account of early season growing

445   conditions. A framework for a crop lodging decision support system known as CROPFALL

446   has been described by Berry et al. (2019). This decision support system is designed to

447   integrate a lodging model with remote sensing information to inform crop husbandry

448   decisions on a field-by-field basis and on a metre-by-metre basis, thereby enabling precision

449   application of crop inputs.

450

6. Conclusions

452   The model of maize lodging risk described in this paper has been shown to calculate

453   plausible failure wind speeds and the model's calculations of the effects of plant population

454   and N fertiliser on lodging risk were consistent with published observations. Further work is

455   required to test the model's output against observations of natural lodging, but the results

456   give confidence that the lodging model can be used to better understand the effect of crop

457   husbandry decisions on lodging risk. This will help farmers and crop advisors to develop crop

458   husbandry strategies for minimising lodging risk. Leaf area index measured at leaf 4, 6 or 8

459   stages was shown to be a good indicator of the future values of the plant characters associated

460   with lodging that are used as the lodging model inputs. This opens up the potential to develop

461   the lodging model to predict lodging risk early enough in the growing season to allow

462   farmers to make tactical agronomic decisions to minimise lodging risk. A sensitivity analysis

463   showed that variation in stem strength and the spread of the root plate are the most important

464   characteristics that influence the risk of stem and root lodging, therefore plant breeding and

465   crop husbandry should focus on maximising these traits.

466

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References

473 Arnold, J. M. and Josephson, L. M., 1975. Inheritance of stalk quality characteristics in

474 maize. Crop Sci. 15, 338–340.

475 http://dx.doi.org/10.2135/cropsci1975.0011183X001500030017x

476 Baker, C.J., Berry, P.M., Spink, J.H., Sylvester-Bradley, R., Griffin, J.M., Scott, R.K. and

477 Clare, R.W., 1998. A method for the assessment of the risk of wheat lodging. *Journal of*

478 *Theoretical Biology* 194, 587-603.

479 Baker, C.J., Sterling, M. and Berry, P.M. 2014. A generalised model of lodging. *Journal of*

480 *Theoretical Biology* 363, 1-12. doi: 10.1016/j.jtbi.2014.07.032.

481 Berry, P.M., Griffin, J.M., Sylvester-Bradley, R., Scott, R.K., Spink, J.H., Baker, C.J., and

482 Clare, R.W., 2000. Controlling plant form through husbandry to minimise lodging in wheat.

483 *Field Crops Research* 67, 59-81.

484 Berry, P.M., Sterling, M., Baker, C.J., Spink, J.H., Sparkes, D.L., 2003. A calibrated model

485 of wheat lodging compared with field measurements. *Agricultural and Forest Meteorology*.

486 119, 167-180.

487 Berry, P.M., Sterling, M., Spink, J.H. Baker, C.J., Sylvester-Bradley, R., Mooney, S., Tams,

488 A., Ennos, A.R. 2004. Understanding and reducing lodging in cereals. *Advances in Agronomy*

489 84, 215-269.

490 Berry, P.M. and Spink, J.H., 2009. Understanding the effect of a triazole with anti-gibberellin

491 activity on the growth and yield of oilseed rape (Brassica napus). Journal of Agricultural

492 Science, Cambridge 147, 273-285.

493   Berry, P., Blackburn, A., Sterling, M., Miao, Y., Hatley, D., Gullick, D., Joseph, G., Whyatt,

494   D., Soper, D., Murray, J., Baker, C., 2019. A multi-disciplinary approach for the precision

495   management of lodging risk. 12th European Conference of Precision Agriculture,

496   Montpellier, p683-687 Wageningen Academic Publishers.

497   Colbert, T.R., Darrah, L.L., Zuber, M.S., 1984. Effect of recurrent selection for stalk crushing

498   strength on agronomic characteristics and soluble stalk solids in maize. Crop Science, 24,

499   473–478.

500   Cook, N.J., 1985. The designer's guide to wind loading on building structures. Part 1, BRE,

501   Butteworths.

502   Ennos, A.R., Crook, M.J., Grimshaw, C., 1993. The anchorage mechanics of maize (*Zea*

503   *mays*). *Journal of Experimental Botany* 44, 147-153.

504   Fincher, R.R., Darrah, L.L., Zuber, M.S., 1985. Root development in maize as measured by

505   vertical root-pulling resistance. Maydica, 30, 383–394.

506   Flint-Garcia, S.A., Jampatong, C., Darrah, L.L., McMullen, M.D., 2003. Quantitative trait

507   locus analysis of stalk strength in four maize populations. Crop Sci. 43:13–22.

508   http//dx.doi.org/10.2135/cropsci2003.0013

509   Fouéré, A., Pellerin, S., Duparque, A., 1995. A portable electronic device for evaluating root

510   lodging resistance in maize. Agronomy Journal, 87, 1020-1024.

511   Griffin, S. and Hollis, J. (2017). Plant growth regulators on winter wheat – yield benefits of

512   variable rate application. Advances in Animal Biosciences: Precision Agriculture (ECPA)

513   2017, (2017), 8:2, pp 233–237 doi:10.1017/S2040470017000267.

514 Guo, Q., Chen, R., Ma, L., Sun, H., Weng, M., Li, S., Hu, J., 2019. Classification of corn

515 stalk lodging resistance using equivalent forces combined with SVD algorithm. Appl. Sci., 9,

516 640; http//dx.doi.org:10.3390/app9040640

517 Hu, H., Liu, W., Fu, Z., Homann, L. Technow, F., Wang, H., Song, C., Li, S., Melchinger,

518 A.E., Chen, S., 2013. QTL mapping of stalk bending strength in a recombinant inbred line

519 maize population. Theor. Appl. Genet. 126,2257-2266

520 Huang, L., Qiao, J.F., Liu, J.B., Xia, L.K., Zhu, W.H., Li, C., Zhou, Q.W., 2015. Research on

521 the relationship between maize lodging resistance and grain mechanically harvesting qualities

522 in different planting density. Acta Agriculturae Boreali-Sinica, 30, 198–201. (Mandarin)

523 Joseph, G.M.D., Mohammedi, M., Sterling, M., Baker, C., Gillmeier, S.G., Soper, D., Jesson,

524 M., Blackburn, A., Whyatt, D., Gullick, D., Murray, J., Berry, P., Hatley, D., Finnan, J.,

525 2020. Determination of crop dynamic and aerodynamic parameters for lodging prediction.

526 Journal of Wind Engineering & Industrial Dynamics 202,

527 https://dx.doi.org/10.1016/j.jweia.2020.104169.

528 Jun, X., Rui-zhi, X., Wang-feng, Z., Ke-ru, W., Peng, H., Bo, M., Ling, G., Shaokun. L.,

529 2017. Research progress on reduced lodging of high-yield and -density maize. Journal of

530 Integrative Agriculture 2017, 16(12): 2717–2725.

531 Kamara, A.Y., Kling, J.G., Menkir, A., Ibikunle, O., 2003. Association of vertical root-

532 pulling resistance with root lodging and grain yield in selected S1 maize lines derived from a

533 tropical low nitrogen population. Journal of Agronomy & Crop Science, 189, 129–135.

534 Li, K., Yan, J., Li, J., 2014. Genetic architecture of rind penetrometer resistance in two maize

535 recombinant inbred line populations. BMC Plant Biol. 14, 152.

536   Li, S.Y., Ma, W., Peng, J.Y., Chen, Z. M., 2015a. Study on yield loss of summer maize due

537   to lodging at the big flare stage and grain filling stage. Scientia Agricultura Sinica, 19, 3952–

538   3964. (Chinese text)

539   Li S Y, Wang Y X, Hu C D, Yan Y. 2015b. Effect of strong wind lodging at pre- and post-

540   tasseling stages on growth and yield of summer maize. Chinese Journal of Applied Ecology,

541   26, 2405–2413. (Chinese text)

542   Liu, S., Song, F., Liu, F., Zhu, X., Xu, H., 2012. Effect of Planting Density on Root Lodging

543   Resistance and Its relationship to Nodal Root Growth Characteristics in Maize (*Zea mays* L.).

544   Journal of Agricultural Science 4, 182-189.

545   Mohammadi, R., Finnan, J., Sterling, M. and Baker C. J., 2020. A calibrated oat lodging

546   model compared with agronomic measurements. Field Crops Research. 225 107784.

547   http://doi.org.10.1016/j.fcr.2020.107784.

548   Peng, D.L., Chen, X.G., Yin, Y.P., Lu, K.L., Yang, W.B., Tang, Y.H., Wang, Z.L., 2014.

549   Lodging resistance of winter wheat (*Triticum aestivum* L.): Lignin accumulation and its

550   related enzymes activities due to the application of paclobutrazol or gibberellin acid. Field

551   Crops Research, 157: 1–7.

552   Shengqun, Liu., Fengbin, Song., Fulai, Liu., Xiancan, Zhu., Haibo, Xu., 2012. Effect of

553   Planting Density on Root Lodging Resistance and Its Relationship to Nodal Root Growth

554   Characteristics in Maize (*Zea mays* L.) Journal of Agricultural Science; Vol. 4, No. 12; 2012.

555   Sher, A., Khan, A., Jin Cai, L., Ahmad, M., Asharf, U. and Ali Jamoro, S., 2017. Response of

556   Maize Grown Under High Plant Density; Performance, Issues and Management - A Critical

557   Review. Advances in Crop Science and Technology, 5, 1-8. http://doi.org/10.4172/2329-

558   8863.1000275.

559   Shi, D., Li, Y., Zhang, J., Liu, P., Zhao, B., Dong, S., 2016. Effects of plant density and

560   nitrogen rate on lodging-related stalk traits of summer maize. Plant Soil Environment 62,

561   299-306.

562   Shekoofa, A., Emam, Y., 2008. Plant growth regulator (ethephon) alters maize (*Zea Mays* L.)

563   growth, water use and grain yield under water stress. Journal of Agronomy 7, 41-48.

564   Spitzer, T., Misa, P., Bilovsky, J., Kazda, J., 2015. Management of Maize Stand Height using

565   Growth Regulators. Plant Protection Science 51, 223-230.

566   Sposaro, M.M., Chimenti, C.A., Hall, A.J., 2008. Root lodging in sunflower. Variations in

567   anchorage strength across genotypes, soil types, crop population densities and crop

568   developmental stages. Field Crops Res. 106, 179–186.

569   Sporoso, M.M., Berry, P.M., Sterling, M., Hall, A.J., Chimenti, C.A., 2010. Modelling root

570   and stem lodging in sunflowers. Field Crops Research 119, 125-134.

571   Wen, W., Gu, S., Xiao, B., Wang, C., Wang, J., Ma, L., Wang, Y., Lu, X., Yu, Z., Zhang, Y.,

572   Du, J., Guo, X., 2019. In situ evaluation of stalk lodging resistance for different maize (*Zea*

573   *mays* L.) cultivars using a mobile wind machine. Plant Methods, 15, 1-16.

574   http://dx.doi.org/10.1186/s13007-019-0481-1.

575   Xia, T., Miao, Y., Wu, D., Shao, H., Khosla, R., M, G., 2016. Active optical sensing of spring

576   maize for in-season diagnosis of nitrogen status based on nitrogen nutrition index. Remote

577   Sensing, 8(7), 605.

578   Xue, J., Xie, R., Zhang, W., Wang, K., Hou, P, Ming, B., Gou, L., Li, S., 2017. Research

579   progress on reduced lodging of high-yield and -density maize. Journal of Integrative

580   Agriculture. 16(12): 2717–2725.