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A generalised model of crop lodging

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HIGHLIGHTS

- A generalised model is presented to describe lodging for isolated plants and plants in canopies.
- The model results in simple expressions for the bending moment along the length of the plant stem.
- The analysis identifies regions of lodging and non-lodging in the rainfall/wind velocity plane.
- Lodging risk can be calculated for any combination of rain/wind/soil and plant characteristics.

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ABSTRACT

The lodging of cereal crops due to high wind and rain is of considerable significance in many parts of the world, leading to major economic losses and yield reductions. In earlier papers the authors have developed a model of the lodging of winter wheat that identified the major parameters of the problem and enabled the relationship between root and stem lodging to be examined. It has formed the basis of a methodology used in the UK for guidance to farmers and agronomists on ways of reducing lodging risk. However the authors would be the first to acknowledge that there are limitations to the model that make it difficult to apply for a wide range of crops – particularly in the specification of the wind field and the root/soil interaction, and in allowing for stem lodging elsewhere than at the base of the stem. This paper thus describes the development of a generalised model that overcomes these shortcomings. After a discussion of the lodging phenomenon in general and a description of the earlier work, the basis of the new model is set out, based upon a mechanical model of the wind/plant/soil interactions that capture most of the important physical processes. The manner in which this model can be applied to clarify the nature of the lodging process and calculate lodging risk through a simple graphical formulation is discussed. In particular simple formulae are defined for lodging risk that are functions of a small number of dimensionless variables with identified physical meanings. The model is then applied to the lodging of wheat, oat and oilseed rape crops and considers the sensitivity of the risk calculations to uncertainties in the model parameters. In general it is suggested that the risk of lodging can be determined from very simple functions of dimensionless stem and root lodging velocities.

1. Introduction

Lodging, defined as the permanent displacement of plant stems from their vertical position, is a persistent problem for many crop species throughout the world, especially in regions where crops are irrigated or where rainfall and high winds are common. As a result lodging resistance is considered as one of the highest priorities for plant breeders worldwide (Reynolds et al., 2008). In the UK lodging is a particular problem in wheat, barley, oats and oilseed rape (Fig. 1). It has been shown that severe lodging years occur, on average, every 3–4 years when 16% of the wheat area and 35% of the oilseed rape areas are lodged (Berry et al., 1998, 2013). Yield losses from lodging in cereal crops and oilseed rape typically can be 25%, but can be up to 75% if lodging occurs early in the season (Berry and Spink, 2012; Berry et al., 2013). The cost of lodging from yield losses in a severe lodging year has been estimated at £105 million for wheat and £64 million for oilseed rape (Berry, 2013). These estimates do not include the additional costs of greater grain drying, loss of bread making quality and longer harvesting time. Lodging in the other major UK cereals, barley and oats, is generally considered to be more prevalent than in wheat. If similar lodging costs per hectare are assumed for these cereal species as for wheat, then the total cost of lodging in a severe lodging year in the UK is conservatively estimated at £200 million, or approximately £60 million per year on average. Farmers

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Nomenclature

a	stem radius
A_{CF}	plant drag area for an isolated plant or the plant shear area for a plant in a canopy
c	clay content
C	damping coefficient per plant due to stem material properties
d	effective root ball diameter
E	Young's modulus of the stem
f	moisture content at field capacity
f_n	natural frequency of crop oscillation
F	wind induced force on a plant
$\overline{F}$	mean wind force value
F'	amplitude of the fluctuating wind force
g_{MB}	gust factor of broad banded stem moment
g_{MR}	gust factor of resonant stem moment
i	daily rainfall
i_o	reference daily rainfall
i_s	saturation rainfall
I	turbulence intensity
I_A	second moment of area of the stem
K	damping coefficient per plant due to canopy interactions
k	wave number
l	length of stem
L	depth of the anchorage rooting system
m	mean daily rainfall
$\tilde{m}$	m/i_0
M	moment on stem
$\overline{M}$	mean moment on stem
M'	fluctuating moment on stem
$\hat{M}$	peak moment on stem
n	number of stems per plant
p	number of plants per unit area
$p(i)$	rainfall probability density function
$p(\overline{U})$	wind probability density function
R	lodging risk
s	soil shear strength
s_D	soil shear strength at the permanent wilting point
s_w	soil shear strength at field capacity
S_M	stem moment spectrum
S_U	wind spectrum
t	stem wall thickness
T	time
$\overline{U}$	mean velocity
$\overline{U}_{LR}$	root lodging velocity
$\overline{U}_{LS}$	stem lodging velocity
$\overline{U}_S$	saturation velocity
$\tilde{U}_{LR}$	$\overline{U}_{LR}/\lambda$
$\tilde{U}_{LS}$	$\overline{U}_{LS}/\lambda$
$\tilde{U}_S$	$\overline{U}_S/\lambda$
v	empirical visual score
V_{gR}	root lodging velocity from Berry et al. (2003)
V_{gS}	stem lodging velocity from Berry et al. (2003)
w	moisture content at the permanent wilting point
x	distance up the stem from the ground
X	height of the centre of mass of the crop canopy
y	displacement of the stem at height x
Y	displacement of the top of the stem
z	distance in the y direction from a fixed point at the edge of the crop
z_0	surface roughness length
α	dimensionless parameter in Eq. (6)
γ	constant in Eq. (25)
ϵ	honami constant
η	wave velocity
θ	damping ratio
λ	wind pdf parameter
μ	mass of the unit area of the canopy
ρ	density of air
ρ_s	density of the soil
ρ_w	density of water
σ	stem yield stress
σ_{MB}	broad banded moment standard deviation
σ_{MR}	resonant moment standard deviation
τ	averaging time
ω	radial frequency

attempt to reduce the risk of lodging by using lodging resistant cultivars and by using chemical plant growth regulators (PGRs). Little progress has been made in breeding cereal varieties with greater lodging resistance since the introduction of semi-dwarfing genes during the 1970s and 80s, and there is evidence in wheat that the lodging resistance of new varieties may in fact be increasing because yield potential is increasing whilst height remains the same (Kendall et al., 2013). PGRs are used on the majority of UK cereal and oilseed rape crops. However, in future the number of products available may become restricted as a result of changing legislation in Europe (revision of 91/414/EEC). Additionally some oat markets restrict the use of PGRs such as chlormequat to minimise the risk of chemical residues in the grain.

The lodging of winter wheat was considered in a series of papers by the authors in the early 2000s (Baker et al., 1998, Berry et al., 2000, 2003, Sterling et al., 2003), through the development of a model of the wheat lodging process, ultimately derived from that developed by Baker (1995), and this has since underpinned much of the current understanding of wheat lodging control. For example, it was used to show that two types of lodging (stem and root) are both important. Unexpectedly it identified variation in stem and anchorage strength as very important determinants of lodging resistance and this led to work with wheat breeders to investigate genetic markers for these traits. The wheat lodging model also underpins the most comprehensive guide that growers and agronomists use to minimise lodging risk (Spink and Berry, 2005) as well as being used by the agricultural industry to quantify the effect of PGRs on lodging risk. This work involved a series of field tests to observe and measure the lodging phenomenon, using a mobile wind tunnel that was placed over field grown crops (Sterling et al., 2003). The results from these tests were used to develop a simple mathematical model of the lodging process that allowed the lodging wind speeds to be determined for crops of different types. This model assumed that the wheat plant can be represented by a two mass model connected by a weightless stem. The upper mass corresponds to the ear, whilst the lower mass corresponds to the root ball. A wind force due to a step change in wind speed is applied to the upper mass to cause displacement of the stem, which is resisted by the anchorage characteristics of the root mass. This allows the bending moment at the base of the stem to be determined, which is then compared with the strength at the base of the stem, or the root failure moment to determine whether or not lodging occurs. This model has been used to provide a method of quantifying how variation in field and plant characteristics affect lodging risk that would allow PGR use to be targeted more precisely.

However, as noted above, winter wheat is not the only cereal crop to undergo lodging in adverse conditions and significant lodging has been observed in barley, oats and oilseed rape. Now