Development and validation of a model of lodging for sunflower

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ABSTRACT

Root and stem lodging cause significant yield losses in sunflower (*Helianthus annuus* L.) production in Argentina. Lodging is defined as the permanent displacement of the stem from its vertical position without any possibility of recovery. Few studies have investigated the mechanistic processes of root or stem lodging and not one has attempted to interrelate the complex interactions between climate and soil variables, husbandry practices and plant characteristics for sunflower lodging. A lodging model was developed for wheat and barley and can be used as a basis for a sunflower lodging model. The objectives of this work are to develop a root/stem lodging model for sunflower and to validate it. The root lodging model calculates the root failure wind speed using as its main variable the root plate diameter. The thickness of the epidermis+cortex measured in the lower third of the stem was the main variable used as input by the stem lodging model for the calculation of the stem failure wind speed. This model was tested against individual field experiments, in which natural root or stem lodging had occurred at different crop development stages under different husbandry practices, and it could recreate the differences observed in the field between hybrids and crop population densities in relation to lodging susceptibility. A parametric analysis showed the root plate diameter and epidermis+cortex as the main variables of the model and indicated that sunflower could be more susceptible to root than stem lodging.

Key words: epidermis+cortex – failure wind speed – model testing – root lodging – root plate diameter – stem lodging.

INTRODUCTION

Root and stem lodging cause significant yield losses in sunflower (*Helianthus annuus* L.) production in Argentina. About 10% of sunflower crop lodges annually, representing an estimated loss of US$40 million (Bragachini et al., 2001) due to the impossibility of harvesting the lodged plants. Lodging is defined as the permanent displacement of the stem from its vertical position without any possibility of recovery.

Root lodging is usually associated with rain (Baker et al., 1998) that weakens plant soil-root system (Pinthus, 1973) combined with a wind-induced force acting on the upper sections of the plant (root failure wind speed) that result in a bending moment at its base that exceeds the root failure moment (Berry et al., 2004). Few studies have investigated the mechanistic processes of root or stem lodging in sunflower. Ennos et al. (1993) observed that the most important anchorage component in sunflower was the resistance to the pulling of the roots on the windward side of the plant. Sposaro et al. (2008) found that anchorage strength was determined by the size of the root plate diameter. Stem lodging occurs when wind exerts a force which breaks the stem at its base (stem failure wind speed) that exceeds the stem failure moment. No studies have attempted to interrelate the complex interactions between climate and soil variables, husbandry practices and plant characteristics for sunflower lodging.

Models of lodging have been developed for wheat (Baker et al., 1998; Berry et al., 2003a) and more recently for barley (Berry et al., 2006). By considering the cereal plants as acting as a damped harmonic oscillator subject to a stepped input (Baker, 1995), these models calculate the wind-induced base-bending moment (leverage) of a shoot from plant characteristics. The calculated base bending moment is compared with the failure moments (strength at the point of failure) of the stem base and of the anchorage system to estimate the risk of stem and root lodging, respectively. Although some of the principles of the wheat and barley model could be the same for sunflower, other traits and differences between these crops must be considered. There are important issues that have to be taken into account for a sunflower model. It must firstly be investigated as to whether the sunflower shoot behaves as a damped harmonic oscillator. The area of the plant that is loaded by the wind is very different from cereals because the capitulum is disc shaped and the leaves present a much greater area. The importance of the root plate diameter in lodging susceptibility has recently been studied (Sposaro et al., 2008). It is also uncertain whether the stem has the strength properties of a cylinder or whether the central pith provides significant strength. It is also possible that there are changes in stem internal anatomy during grain filling due to remobilization.

The objectives of this work are to develop a root/stem lodging model for sunflower and to validate it. This model was tested against individual field experiments in which natural root or stem lodging had occurred at different crop development stages under various crop population densities.

MATERIALS AND METHODS

In order to develop the lodging model a method to estimate the root and stem failure moments was developed during various years of experimentation.

Measurements of root failure moment (B_R)

Root failure moment values (B_R) were obtained by Sposaro et al. (2008). These measurements were carried out for two commercial hybrids (CF29 and Zenit), four crop population densities (3, 5.6, 10 and 16 plant m^{-2}) and three developmental stages (R2, R5.9 and R8 on Schneiter and Miller [1981] scale) in two different soil types (Typic Argiudoll and Typic Hapludoll) during three years.

Measurements of stem failure moment (B_S)

The values of stem failure moments (B_S) needed for the lodging model were obtained during two years of experiments: 2004/05 (E1) and 2005/06 (E2). In both experiments, two hybrids (Experimental Stay green (SG), Advanta Semillas, Argentina and Zenit, Sursem, Argentina), with different stem lodging susceptibility were planted using two plant population densities (5.6 plants m^{-2} [E1] and to 5.6, 10 and 16 plants m^{-2} [E2]) A randomized complete block design with three replications was used.

Measurements were performed at three stages of crop development: when the grain reached: a) 50% of its final dry grain weight (R7); b) 90% of its final dry grain weight (R8); and c) harvest maturity. These stages were selected because it is recognized that during grain filling and harvest maturity are the most stem lodging susceptible stages in sunflower (Abelardo de la Vega, personal communication).

An instrument especially constructed, the same used by Sposaro et al. (2008), was used to measure the force (F, N) required to induce stem lodging by pushing individual stems gradually from their vertical position until stem breakage occurred. The height of the bar that pushed the plant was adjustable, and set at 60% of the plant height (h). The stem failure moment (B_S, N m, i.e., the moment (Nm) needed to induce stem lodging) was obtained as the product of the force F (N) by $0.6h$ (plant height, m). Once the stem broke, the thickness of the epidermis plus the cortex (Ep+Co, m) was measured at the place where the stem failure occurred.

Plant area expected to be hit by wind gusts (A)

In order to understand how to estimate the area of the plant that is hit by wind gusts, we studied the shape of the leaves and capitulum through development. We measured the diameter and thickness of the capitulum and the length and width of the leaves in the upper third of the stem. The area formed by the leaves and the capitulum in the upper third of the plant was used for the estimation of the area that hits wind gusts.

Plant natural frequency (n)

Natural frequency (n) measurements were carried out for each hybrid at different stages of development. Each individual plant was pulled 10º from its vertical position and allowed to oscillate freely. The time taken for each plant to stop oscillating and the number of oscillations were recorded, and then transformed into number of oscillations per second (Hz) known as natural frequency (Berry et al., 2003b).

Model development

The sunflower model was developed based on exiting models for wheat (Baker et al., 1998; Berry et al., 2003a; Sterling et al., 2003) and more recently for barley (Berry et al., 2006). By considering the plants to act as a damped harmonic oscillator subject to a stepped input (Baker, 1995) these models calculate the wind-induced base-bending moment (leverage) of a shoot from B_R, B_S and plant characteristics. The calculated base bending moment is compared with the failure moments (strength at the point of failure) of the stem base and of the anchorage system to estimate the risk of stem and root lodging, respectively.

Point of application of the wind

In keeping with the work of Finnigan (2000), it was assumed that the top one third of the plant experienced significant wind loading. Hence the overall point of application was changed to 5h/6, where *h* is the height of the plant; this differs from the wheat model which assumes the point of application is at the centre of gravity.

Model validation

During season 2006/07 four meteorological stations (Vantage Pro2^{TM}, Davis Instruments Corp. 3465 Diablo Ave. Hayward, California 94545 USA) were installed at four different locations: Faculty of Agronomy, University of Buenos Aires (FAUBA), Advanta Semillas Research Centre, Venado Tuerto (VT), Daireaux, Buenos Aires; General Pico, La Pampa. At FAUBA, the meteorological station was installed during 2005/06, too. Three sunflower hybrids with different root or stem lodging susceptibility by four crop population densities were implanted at the four sites. The stations registered precipitation, wind speed and direction. At each location the percentage of root or stem lodging was recorded and was represented as a lodging index. The lodging index values are between 0 (no lodging) and 1 (the entire plot lodged).

RESULTS AND DISCUSSION

Methods for calculating root and stem failure wind speed

The root failure wind speed (minimum wind speed that could cause root lodging) V_{gR} (m s^{-1}) can be calculated using Eq. 1:

$$V_{gR} = \sqrt{\frac{2B_R}{\left(\rho A C_d h\left(1+\left(g/(2\pi n)^2 h\right)\right)\left(1+e^{-\pi\delta(\sin(\pi/4)/(\pi/4))}\right)\right)}} \quad \text{Eq. 1}$$

Where B_R = 0.2382x, being x the root plate diameter cubed multiplied by the soil shear strength (sd^3, Nm, i.e. anchorage strength) (Fig. 1). This robust association between B_R and anchorage strength (sd^3) that held across hybrids, soil types, stages of development and crop population densities (Sposaro et al., 2008) allows a comparison to be made with the same relationship used in the previous lodging model for other crops, specifically wheat and barley. In wheat, the slope of the B_R / sd^3 relationship was 0.39 (Crook and Ennos, 1993) or 0.43 (Baker et al., 1998), while that for barley was 0.58 (Berry et al., 2006). These values contrast with the slope of 0.24 we found in sunflower (Fig. 4), suggesting that sunflower has an inherently lower B_R than the winter cereals for a given root plate diameter (Sposaro et al., 2008).

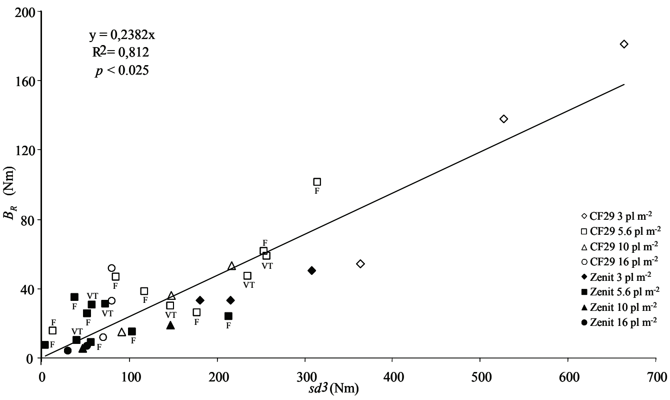

Fig. 1. Relation between B_R (Root failure moment) (Nm) and sd^3 (Plant anchorage) (Nm). Each point is the value for each d^3 (root plate diameter cubed) multiplied by s (soil shear strength) corresponding to four plant densities (3-5.6-10 and 16 plants m^{-2}), two genotypes (Zenit and CF29) and two soil types FAUBA (F), Typic Argiudoll and Venado Tuerto (VT) Typic Hapludoll against each respective value of B_R (from Sposaro et al., 2008).

In the same way the stem failure wind speed (minimum wind speed that could cause stem buckling) V_{gS} (m s^{-1}) can be calculated using Eq. 2:

$$V_{gS} = \sqrt{\frac{2B_S}{\left(\rho A C_d h\right)\left(1+\left(g/\left(2\pi n\right)^2 h\right)\right)\left(1+e^{-\pi\delta\left(\sin(\pi/4)/(\pi/4)\right)}\right)}} \quad \text{Eq. 2}$$

Where $B_S = 5980.2x$, being x the Ep + Co (m) measured in the lower third of the stem (Fig. 2).

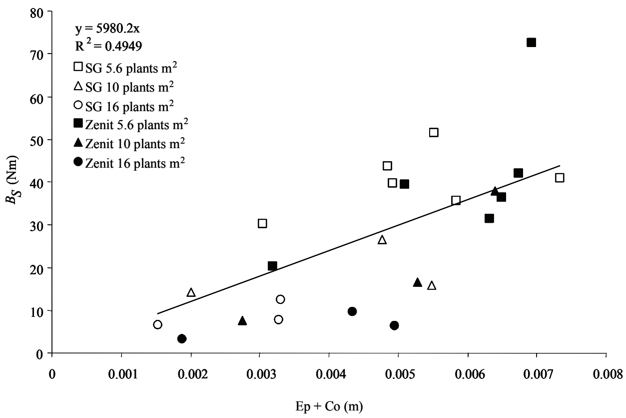

Fig. 2. Relation between B_S (Stem failure moment) (Nm) and Ep+Co (m) from lower third of the stem.

This relationship shows that hybrids with a better maintenance of the stem internal structures during grain filling (i.e. Stay green hybrids) could be more resistant to stem failure at these phenological stages. These results are important in determining the importance of the behavior of the stem as a cylinder providing significant resistance to buckling. Our results are consistent with those of Berry et al. (2003) and Berry et al. (2006) for wheat and barley, respectively.

In Eq. 1 and 2, n is the measured plant natural frequency, A the area expected to be hit by wind gusts, h the plant height, ρ air density, C_d sunflower drag coefficient (0.5), δ the damping ratio (0.08) and g the acceleration due to gravity (9.81 m s^{-2}).

Model validation

The model has been tested against various lodging events observed in sunflower experimental plots. Four storms that caused root lodging were recorded: 30/01/05, 17/12/06 (this lodging occurred at a neighbor's experimental plot [Hybrid 1] at FAUBA and was recorded too), 03/03/2007 at FAUBA and 01/12/06 at VT. Stem lodging was registered: 02/03/2007 at FAUBA. The plant parameters (mean of 10 plants per plot) were used with soil information to predict the failure wind speed for each experimental plot lodged. Table 1 shows the recorded and predicted root or stem failure wind speed and the lodging index for each hybrid, crop population density at the location where lodging occurred. If the recorded failure wind speeds were greater than those predicted, root or stem lodging could be expected for that plot. It is remarkable that the predictions of the model recreated the differences in lodging susceptibility between hybrids and crop population densities (Sposaro et al., 2008). For Zenit and CF29 the predicted root failure wind speed diminished when crop population density increased while for Stay green hybrid (SG) stayed stable, which was expected due to the maintenance of the integrity of the Ep+Co of the stem.

The results of the failure wind speed for root or stem lodging are consistent with the lodging index recorded in each combination of hybrid and crop population density. In the cases when the recorded failure wind speed was less or similar than that predicted by the model minimum or no lodging was recorded, and when the differences between recorded and predicted failure wind speed were greater, the recorded lodging index increased.

Parametric analysis

A parametric analysis was made in order to describe what the response of predicted failure wind speed was with changes in each separated variable of the model and to detect which one was the most important in determining lodging susceptibility. Each parameter varied throughout its entire range (between percentile 0 and 100) of values for all hybrids, stages of development and crop population densities.

Table 1. Lodging index, recorded and predicted (n = 10; ± 1 standard error) root or stem lodging wind speed and type of lodging (R, root; S, stem), for the lodged plots at different location, dates and crop population densities.

Hybrid	Crop population density (plant m^{-2})	Date	Location	Type of lodging	Lodging index	Recorded failure wind speed (m s^{-1})	Predicted failure wind speed (m s^{-1})
SG	5.6	30/01/2005	FAUBA	R	0.5	14.7	6.6 ± 0.7
Zenit	5.6	30/01/2005	FAUBA	R	0.8	14.7	5.7 ± 0.56
CF29	5.6	30/01/2005	FAUBA	R	0	14.7	14.4 ± 0.06
Zenit	3	01/12/2006	VT	R	0.3	13	7.4 ± 0.77
Zenit	5.6	01/12/2006	VT	R	0.37	13	6.1 ± 0.65
Zenit	10	01/12/2006	VT	R	0.6	13	5.6 ± 0.48
Zenit	16	01/12/2006	VT	R	0.85	13	4.3 ± 0.22
CF29	3	01/12/2006	VT	R	0	13	25.2 ± 1.22
CF29	5.6	01/12/2006	VT	R	0	13	16.7 ± 0.85
CF29	10	01/12/2006	VT	R	0.05	13	12.1 ± 0.27
CF29	16	01/12/2006	VT	R	0.05	13	11.5 ± 0.69
Hybrid 1	5.6	17/12/2006	FAUBA	R	1	14.8	6.1 ± 0.52
Zenit	3	03/03/2007	FAUBA	R	0	8.3	8.8 ± 0.78
Zenit	5.6	03/03/2007	FAUBA	R	0.3	8.3	7 ± 0.46
Zenit	10	03/03/2007	FAUBA	R	0.5	8.3	2.6 ± 0.25
Zenit	16	03/03/2007	FAUBA	R	0.95	8.3	2.5 ± 0.24
CF29	3	03/03/2007	FAUBA	R	0	8.3	12.7 ± 0.9
CF29	5.6	03/03/2007	FAUBA	R	0	8.3	10.9 ± 0.57
CF29	10	03/03/2007	FAUBA	R	0.05	8.3	8.6 ± 0.21
CF29	16	03/03/2007	FAUBA	R	0.1	8.3	7.5 ± 1.2
Zenit	5.6	02/03/2007	FAUBA	S	0	8.9	9.9 ± 0.39
Zenit	10	02/03/2007	FAUBA	S	0.95	8.9	5.3 ± 0.61
Zenit	16	02/03/2007	FAUBA	S	0.5	8.9	5.9 ± 0.65
SG	5.6	02/03/2007	FAUBA	S	0	8.9	8.7 ± 0.3
SG	10	02/03/2007	FAUBA	S	0	8.9	8.9 ± 0.48
SG	16	02/03/2007	FAUBA	S	0	8.9	8.9 ± 0.66

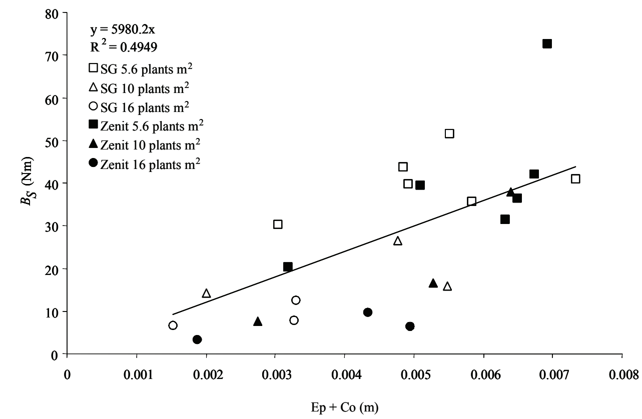

Fig. 3. Parametric analysis for root and stem lodging model. a) Predicted root failure wind speed (m s^{-1}) and b) stem failure wind speed (m s^{-1}) for variations between 0 (minimum value) and 1 (maximum value) in model variables: *h*, plant height (m); *A*, area expected to be hit by wind gusts (m^2); *n*, natural frequency (Hz); a) root plate diameter and b) *Ep+Co*, thickness of the epidermis plus the cortex of the stem.

Predicted root failure wind speed (Fig. 3a) was affected mostly by changes in root plate diameter (i.e. root failure wind speed increased in a greater proportion when root plate diameter was higher and decreased when it was lower). Stem failure wind speed (Fig. 3b) was affected mostly by variations in thickness of *Ep+Co* in the same way as the root plate diameter. The area expected to be hit by wind gusts (*A*) was an important variable too for the determination of the failure wind speed, but only when its values were the lowest. Although variations in height (*h*) and natural frequency (*n*) modified the results for failure wind speed, these were of a lesser importance than the other parameters. This is an important finding because most farmers think that plant height is the most important trait that determines lodging susceptibility. These results are similar to those of Berry et al. (2003) for wheat; the root plate diameter and the thickness of the stem wall (i.e. the same as Ep+Co in sunflower) being the most important parameters affecting the predicted failure wind speed. Fig. 3 a) and b) show that the value of the average stem failure wind speed is higher (8.5 m s^{-1}) than the root failure wind speed (7.8 m s^{-1}), indicating that sunflower could be more susceptible to root than stem lodging.

To summarize, the results of this study show, for the first time in sunflower, the developing of a model that can accurately predict the root/stem failure wind speed for crops growing under various husbandry practices (hybrids, crop population densities, soil types). The variables that are inputs of the model can be used in breeding programs to select hybrids that could be more resistant to stem or root lodging.

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