Field Crops Research 119 (2010) 125–134

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Modelling root and stem lodging in sunflower

M.M. Sposaro[a,*], P.M. Berry[b], M. Sterling[c], A.J. Hall[a], C.A. Chimenti[a]

[a] IFEVA, CONICET/Facultad de Agronomía, Universidad de Buenos Aires, Av. San Martín 4453, C1417DSE Buenos Aires, Argentina
[b] ADAS High Mowthorpe, Duggleby, Malton, North Yorkshire YO17 8BP, UK
[c] School of Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

ARTICLE INFO

Article history:
Received 21 November 2009
Received in revised form 28 June 2010
Accepted 30 June 2010

Keywords:
Model
Failure wind speeds
Sensitivity analyses
Helianthus annuus L.

ABSTRACT

Stem and root lodging constitute significant adversities to sunflower (*Helianthus annuus* L.) cropping in Argentina. We have adapted previously developed models of the lodging process in cereals to the particularities of sunflower by using functions, developed using data obtained by mechanical lodging, for the [root failure moment/plant anchorage] and [stem failure moment/thickness of stem wall] relationships, and estimates of plant area loaded by wind gusts. The model uses this information to estimate wind failure speed (i.e., the wind speed at which lodging [stem or root, as appropriate] is expected to occur). The model was tested against information (plant and soil characteristics, measured wind gust velocity immediately preceding rainfall) obtained in 26 naturally lodged plots (6 stem-lodged, 20 root-lodged) which occurred across a network of trials (2 seasons, 4 sites, 3 hybrids, 4 crop population densities, all experiments fitted with automatic meteorological stations). Lodging events took place over a range of crop developmental stages between visible capitulum and harvest maturity. Lodging index (proportion of plants lodged) against the difference between observed and model-estimated wind failure speeds showed that the model had good predictive skill across the range of conditions explored in these experiments and was able to distinguish between hybrids of differential susceptibility to lodging within the same experiment. Sensitivity analyses showed that the principal determinants of lodging susceptibility were root plate diameter, stem wall thickness, and the area of the plant loaded by wind gusts. Within the observed ranges (almost twofold) of stem height and stem natural frequency, these two variables had little influence on lodging susceptibility. We conclude that the model, despite the simplifications incorporated into its structure, provides an effective and useful tool for the integration of the complex factors that determine lodging susceptibility in this species.

1. Introduction

Root and stem lodging (defined as the permanent displacement of the stem from its vertical position) cause important yield losses in sunflower (*Helianthus annuus* L.) production in Argentina. The prostrate capitulae of lodged plants are not retrieved during mechanical harvesting, and about 10% of sunflower crop lodges annually, for an estimated loss of US$40 million (Bragachini et al., 2001). In experimental trials and farmers plots (INTA, 2003) and in published studies (Ennos et al., 1993; Sposaro et al., 2008; Hall et al., 2010) sunflower lodging has been observed to result from failure of the root anchorage system or from tensile failure of the stems. The susceptibility to lodging and its occurrence in stems or roots of crops exposed to high winds depends on complex interactions between the mechanical properties of the stems and the soil–root system that anchors the plants, the shape of the upper sections of the plant that capture wind gusts, and rain. The values of these variables vary throughout crop development, and can change with husbandry practices (e.g., sowing density), genotype, and soil properties. Stem lodging can occur in well-anchored crops when the force applied to the lower portion of the stem exceeds the stem failure moment. Root lodging is usually associated with rain that weakens the anchorage (i.e., the soil–root system) via a reduction in soil strength (Ennos et al., 1993; Sposaro et al., 2008).

The effects of crop development, crop population density and genotype on root lodging susceptibility in sunflower have been studied using artificial lodging (Sposaro et al., 2008). Ennos et al. (1993) observed that the most important anchorage component in sunflower was the resistance to breakage of the roots on the windward side of the plant. Sposaro et al. (2008) found that

* Corresponding author. Present address: Nidera S.A., C.C. 35, 6013, Baigorrita, Buenos Aires, Argentina. Tel.: +54 2362 447036/446825.
E-mail addresses: msposaro@agro.uba.ar (M.M. Sposaro), Pete.Berry@adas.co.uk (P.M. Berry), m.sterling@bham.ac.uk (M. Sterling), hall@agro.uba.ar (A.J. Hall), chimenti@agro.uba.ar (C.A. Chimenti).

0378-4290/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.fcr.2010.06.021

anchorage strength, across genotypes, developmental stages and crop population densities was determined by the spread of the root plate, in agreement with studies on wheat and barley (Crook and Ennos, 1993; Baker et al., 1998; Berry et al., 2006). A study of stem lodging during grain filling using artificial lodging in crops of two sunflower genotypes growing at three crop population densities showed that stem lodging susceptibility increased as harvest maturity approached and at higher crop population densities (Hall et al., 2010). Stem failure yield stress (B_S) was positively related to the thickness of the epidermis plus cortex tissues ($Ep + Co$) close to the base of the stem (Hall et al., 2010). The lack of associations between B_S and the diameter of the friable stem medulla and of the stem diameter found in this study suggests that the sunflower stem functions, in mechanical terms and during the grain filling phase, somewhat like a hollow cylinder. In this, sunflower appears to be similar to species with true hollow stems (e.g., Crook and Ennos, 1994; Berry et al., 2003a,b, 2006).

Models of lodging have been developed 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 as damped harmonic oscillators subject to a stepped wind input (Baker, 1995) these models calculate the wind-induced base-bending moment (leverage) of a shoot from plant characteristics and meteorological data. 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 risks of stem and root lodging, respectively. The stem is considered as a hollow cylinder where the thickness of the stem wall and its material strength are the most important variables that determine stem failure moment (Baker et al., 1998; Berry et al., 2006). In the case of root lodging, the model considers the root plate spread and soil shear strength for the calculation of root failure moment. These models require, as inputs, other variables including the height of the centre of gravity and the natural frequency of the shoot and variables related to the aerodynamic properties of the plant: the area of the ear which captures wind-gust energy, the drag coefficient and damping ratio. These models can be used to estimate root or stem failure wind speeds (V_{gR} and V_{gS}, respectively).

Although recent studies have advanced our understanding of root (Sposaro et al., 2008) and stem lodging (Hall et al., 2010) in sunflower, the lack of an overall framework that can be used to integrate the various determinants of lodging is a serious obstacle to progress in the understanding of the nature of the process and to the formulation of crop management and breeding strategies aimed at minimizing the effects of this adversity on yield. The fact that the yield potential in the sunflower crop is constrained by the need to use crop population densities that are lower than those needed to maximise yield in order to reduce, among other things, susceptibility to lodging (López Pereira et al., 2004) is a further incentive to the formulation of a framework model of the process.

In developing a lodging model for sunflower, the wheat and barley models are helpful as many of the relevant principles also apply to sunflower. However, there are also important species differences which must be accounted for. The area of the sunflower plant that is loaded by the wind is very different to that of cereals because the capitulum is disc shaped and the leaves are much larger. The degree to which the wind loads the capitulum and leaves, which approximates the drag coefficient, is also unknown. Furthermore, there are significant changes in capitulum shape and position with crop development and between genotypes (Knowles, 1978).

The objectives of the work reported here were to develop and test a root/stem lodging model for sunflower, and to use the resulting model to explore the impact of the various determinants of crop lodging susceptibility on the overall process. Relationships between root and stem failure moments and root anchorage strength and stem structure, respectively, required for model development were taken from previous publications (Sposaro et al., 2008; Hall et al., 2010). Dynamics of plant area that is loaded by the wind and plant natural frequency and their responses to genotype, crop development, and crop population density were measured during three experimental seasons. The model was tested using an independent set of field experiments conducted at several sites, crop population densities and genotypes in which natural root or stem lodging occurred at different crop development stages. Rainfall prior to and wind speeds during these lodging events were recorded in the experimental plots.

2. Experimental methods

2.1. Estimation of plant area loaded by wind gusts (A)

Field observations of crop behaviour under gusty conditions at various stages of crop development indicated that substantial deformation of the stem and re-arrangement of leaf positions was limited to the upper third of the plant.

This is consistent with the work of Finnigan (2000), in various species, which assumes that the upper third of the plant could experiment significant wind loading. When exposed to a gust of wind, the leaves of the upper third tend to become organized into a somewhat vertical plane or sail, the shape of which could be approximated by a trapezium. In order to estimate the area involved in the capture of wind gust energy (A) at any given stage of crop development, we assumed that the leaves (laminae only) attached to the upper third of the plant formed a trapezium, this was then simply approximated as: $(B + b) \times h/2$, where B is the sum of the lengths of both leaves of the bottom, b is the sum of the lengths of the apical leaves and h is the sum of the widths of each leaf in the upper third of the plant (Fig. 1a). The capitulum could be represented by a disc of finite thickness which could assume a range of positions (from horizontal, through vertical, to hidden among the upper leaves) as the crop passed through different stages of development (Fig. 1). Fig. 1 summarizes the relationship between estimates of A and crop development as noted in the Schneiter and Miller (1981) development scale. Many sunflower hybrids grown in Argentina have capitulae that "hide" within the upper stratum of the canopy after flowering, but the scheme shown in Fig. 1 can be accommodated to hybrids that remain with erect capitulae (Knowles, 1978) after flowering. It should also be noted that the lower limit of the trapezium, present at flowering, moves upwards after basal leaf senescence progresses beyond that limit, resulting in a decrease in A as development proceeds towards harvest maturity.

Measurements of A were made at the R2, R5.9, R7, and R8 Schneiter and Miller (1981) developmental stages, and at harvest maturity (HM), in a set of six experiments described in Sposaro et al. (2008) (Experiments: E1, E2 and E3) and Hall et al. (2010) (Experiments: E1, E2 and E3). Each experiment involved plots of Zenit (Sursem Argentina) and another hybrid (either CF29 or V70597 (experimental stay green), both from Advanta Semillas Argentina) sown at either three or four crop population densities in the 3–16 plants m^{-2} range. It is not unreasonable to assume that as the wind speed increases, the area of A will decrease as the leaves bend with the wind. However, within the scope of the current study it was difficult to quantify this reduction and the range of wind speeds over which it may occur. Also, it must have taken into account that the lower limit of the trapezium, that represent a portion of this A, moves upwards after basal leaf senescence reaches that limit. Hence, it is acknowledged that our estimates of A must be regarded as approximate. In spite of these uncertainties, we believe our approach to estimating A is consistent with the spirit of the lodging models developed for cereals referred above.