Negative effects of lodging on irrigated sugarcane productivity – an experimental and crop modeling assessment

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Abstract

Lodging lowers the productivity of sugarcane through a reduction in radiation use efficiency and stalk damage. However, there are few reports of experiments specifically designed to quantify effects of lodging in sugarcane. Efforts to model onset and progression of lodging, and the impact on crop productivity, have not been attempted. The objectives of this paper were to quantify effects of lodging on sugarcane and to develop modeling capability in terms of predicting lodging onset, progression and impact. Field experiments with irrigated ratoon crops were conducted at Pongola, South Africa. In one treatment the cane in each plot was allowed to grow through bamboo frames that prevented lodging. In the other treatment, the cane was not supported and could lodge at any stage. The degree of lodging was captured weekly by a rating that ranged from 1 to 9, where 1 = fully erect cane and 9 = completely lodged cane. At harvest estimated recoverable crystal percent (ERC %) of stalks and yield (cane and ERC) was measured for each plot. Lodging resulted in decreased ERC yields of up to 20.6%. An algorithm for simulating lodging when aboveground biomass (including rainfall and irrigation water retained on it) exceeds a variety-specific threshold, and which also considers wind speed and soil water content, was evaluated for predicting the extent and impact of lodging in the Pongola experiments, as well as for four deficit irrigation treatments of a field experiment conducted in Komatipoort, South Africa. The study showed that the onset of lodging was simulated reasonably well for various soil/crop/atmospheric conditions, while the extent of lodging at harvest was simulated very accurately for all crops. Simulated lodging was primarily driven by crop size and lodging events were triggered by rainfall that added weight to the aerial mass of the crop, and reduced the anchoring ability of the soil through saturation of the top soil. More accurate simulation of lodging, and its impacts on yield, will improve the accuracy of yield predictions by crop models, increasing

their value in applications such as crop forecasting, climate change studies and exploring crop improvement and management options.

Keywords: Cane quality, Cane yield, Crop modelling, Lodging, Sugarcane

1. Introduction

Lodging can be defined as the loss of crop erectness due to either stem failure or stool tipping (Berding and Hurney, 2005). Two types of lodging occur in sugarcane namely stem lodging, in which stalks buckle and bend (and often snap), and root lodging (or stool tipping), in which root anchorage fails when they are pulled out of the soil and are sheared from the stool base. It is possible for both types of lodging to occur simultaneously within the same field. Lodging typically occurs in high-yielding crops (fresh cane mass in excess of 100 t/ha) under conditions of wet soil (poor support for roots), wet leaf canopy (altering the crop's centre of gravity) and strong wind (Singh et al., 2002).

In sugarcane lodging typically increases with increasing stalk height (Sharma and Khan, 1984). These authors found high correlations between lodging and stalk height and suggested that resistance to lodging was conferred by short sugarcane stalks. Their results showed that stalk weight and stalk thickness (diameter) at the top of the stalk aggravated lodging. Berding et al. (2005) established correlations between a number of phenotypic descriptors for erectness (stalk height, stalk diameter, stalk population density, leaves per stalk, leaf length and width) of sugarcane and showed that the strongest predictor of lodging was stalk height. These authors concluded that crop erectness could be improved by selecting clones with shorter stalks. However, it was also acknowledged that because of the strong genetic correlation between the traits, selecting for shorter stalks would invariably result in cane yield reductions.

Lodging is known to reduce the productivity of sugarcane through lower biomass production and a reduction in cane quality (Muchow et al., 1995; Singh et al., 2002; Berding and Hurney, 2005). These effects are caused by a reduction in radiation interception, radiation use efficiency, stalk smothering, stalk death and stalk snapping in lodged crops (Muchow et al., 1995; Singh et al., 2002; Park et al., 2005). More labour input is also required to harvest lodged cane and reduced payloads of cane delivered to the mill are common. Mechanical harvesting of lodged cane also results in infield damage to disrupted stools, which causes gaps inside the cane rows (Singh et al., 2002).

A detailed investigation by Park et al. (2005) into the so-called reduced growth phenomenon (RGP) considered the role that lodging may play in this phenomenon. Under conditions of RGP the linear relationship between cumulative intercepted radiation and biomass accumulation becomes uncoupled causing the crop not to attain its full yield potential (van Heerden et al., 2010). Park et al. (2005) cited 95% of potential yield being attained in cases where RGP did not occur compared with only 79% in crops suffering from RGP. Lodging and RGP co-occurred in 16 of the 34 cases studied by these authors. Generally, lodging occurred on average 81 days before the onset of RGP, which indicates that lodging could have been a contributing factor. However, despite lodging, RGP did not occur in nine of the 34 cases studied. This suggests that lodging does not necessarily lead to reduced growth or that it first needs to interact with other environmental factors.

There are very few reports of field trials specifically designed to quantify the effects of lodging on sugarcane productivity, mainly due to the practical difficulties in conducting these type of studies. Hurney and Berding (2000) showed, from paired-within-plot comparisons of erect and lodged (physically pushed over by hand) stalks, that lodging reduced sugar content by 1.2 units, or 9%. Lodging also caused stalk death and deterioration that resulted in cane yield increase to terminate or even decline (by up to 8%) before harvest.

However, lodging close to harvest had no seriously deleterious effects on yields. In experiments conducted in Australia, sugarcane crops were physically prevented from lodging by means of bamboo scaffolding (Singh et al., 2002). These experiments revealed that prevention of lodging resulted in 11 – 15% and 15 – 35% higher cane and sugar yields respectively.

Attempts to model the onset of lodging in sugarcane crops and the impact of lodging on crop productivity are few. The APSIM-sugar model (Keating et al., 1999) simulates yield reduction due to lodging through a user-specified stalk death rate and reduction in radiation use efficiency. The onset of lodging is also user-specified. The approach is therefore to force model simulation with observed data rather than representing cause/effect relationships. Inman-Bamber et al. (2004) formulated lodging rules in a simulation study with the APSIM model based on various combinations of dry biomass, rainfall and antecedent soil water content thresholds.

The DSSAT-Canegro v4.5 (Singels et al., 2008) and Canesim (Singels, 2007) models have an algorithm for simulating the occurrence of lodging events and their impact on crop processes. Simulated lodging occurs when aboveground biomass (fresh mass plus the estimated mass of rainfall and irrigation water retained on it) exceeds a given threshold. The threshold is variety-specific and also depends on wind speed and water content of the top soil. Lodging is simulated as an incremental process and the extent of lodging at each event is proportional to the magnitude of threshold exceedance. Lodging reduces interception of radiation and radiation use efficiency. Although the work by Singh et al. (2002) shows that different mechanisms contribute to lodging-induced yield reductions, the primary drivers of yield in the crop models are radiation interception and its efficiency of conversion to biomass. This lodging algorithm has not been tested and values of the various parameters (fresh aboveground biomass threshold, wind speed and soil water parameters) were based on anecdotal information. There is therefore a great need to evaluate and possibly refine the lodging algorithm to produce more accurate estimates of the extent of lodging and its impact on crop growth and yield for different varieties under different environmental conditions. A reliable model can be used for calculating lodging risks for different variety-environment-management situations, thereby assisting in the designing of management practices and breeding strategies to minimize lodging impacts.

The objectives of this paper were firstly to quantify the effects of lodging on sugarcane productivity under irrigated conditions, and secondly, to use the experimental evidence acquired from the field experiments to evaluate an existing model for predicting the onset and progression of lodging and its impacts on crop productivity.

2. Materials and methods

Two field experiments were conducted over consecutive seasons at the South African Sugarcane Research Institute's research farm at Pongola (27°24'S, 31°35'E, 308 masl). In the first field experiment lodging was studied in a crop on a May-harvest cycle (autumn). In the second field experiment the following year, lodging was studied in a crop on a December-harvest cycle (summer). These contrasting harvest cycles were selected to best capture most of the climatic conditions that mature crops experience in this production region.

Lodging was also carefully monitored in a field experiment conducted at the South African Sugarcane Research Institute's research farm near Komatipoort (25°37'S, 31°52'E, 187 masl). In this experiment, which was designed to study water stress effects (Rossler, 2014), four different deficit irrigation treatments were applied, leading to different patterns of growth and onset/severity of lodging. The data collected in this experiment were considered useful for model testing.

2.1 Trial details

2.1.1. Field experiment 1 (Pongola – autumn harvest cycle)

A field trial was planted to variety N25 (chosen because of its high propensity for lodging) on 11 September 2008. At planting 300 kg/ha superphosphate and 250 kg/ha urea was applied in the furrow followed by a second application of 250/kg ha urea four months later. The plant crop was slashed-back on 31 March 2009 to establish an autumn-harvest crop cycle. The 1st ratoon was fertilised with 480 kg/ha urea applied as two equal split applications two months apart. Fertiliser was applied according to maximum crop requirements (in order to maximise biomass yields which would favour the occurrence of lodging) determined from soil samples taken before planting/slash-back and leaf samples taken from the young crop at an age of 3 - 4 months. The crop was initially irrigated by overhead sprinklers to bring the water in the soil profile to field capacity. Thereafter water was applied by surface drip irrigation to maintain soil moisture content in the top 60 cm of the soil profile between 75 – 95% of field capacity. Soil moisture content was monitored by means of Decagon 10HS soil moisture probes inserted into undisturbed soil at 15 cm and 45 cm depths at each of five positions within the field.

The experiment was a completely randomised design (CRD) with six replications per treatment. Each treatment plot comprised five cane rows 9 m long spaced 1.4 m apart. Plots were separated from each other on all sides by 2 m corridors of bare soil to ensure that lodging later on in the mature crop in one plot would cause the least possible impact on cane growing in adjacent plots. The trial consisted of two treatments. In the control treatment (not-lodged) the cane in each plot was allowed to grow through bamboo frames (Singh et al., 2002) that physically prevented lodging in the older crop. Bamboo poles (± 50 mm in diameter and 4.2 m long) were buried into holes 60 cm deep into the soil at a spacing of 1.5 m along each of the 5 cane rows within a plot. A horizontal layer (tier) of bamboo poles were wired onto the vertical poles at a height of 1.8 m to form a grid of squares through which the young crop eventually grew. In the other treatment (lodged), the cane was not supported and thus free to lodge at any stage. This experimental design enabled accurate quantification of the impact of lodging on cane productivity parameters (Singh et al., 2002).

2.1.2. Field experiment 2 (Pongola – summer harvest cycle)

The second field trial was planted to variety N25 on 23 April 2010. At planting 250 kg/ha MAP and 100 kg/ha urea was applied in the furrow followed by a second application of 200 kg/ha urea 4 months later. The plant crop was slashed-back on 25 November 2010 to establish a summer-harvest crop cycle. The 1st ratoon was fertilised with 200 kg/ha KCl and 450 kg/ha urea applied as two equal split applications one month apart. Irrigation management and experimental design was exactly the same as in field experiment 1 (section 2.1.1.).

2.1.3. Komatipoort field experiment (Rossler, 2014)

A field trial was planted to variety N49 in dual rows spaced 2 m apart, on 8 November 2011 and slashed-back on 23 April 2012 to initiate a first ratoon crop on an autumn-harvest cycle. Four irrigation treatments were applied to this crop with the aim of maintaining plant available soil water (ASW) between 30 and 60% of its capacity (ASWC – plant available soil water content at field capacity) through (1) the tillering phase (T), (2) the stalk elongation phase (SE) and (3) through both tillering and stalk elongation phases (T+SE), while the ASW was maintained above 60% of ASWC in the well-watered control (WW) and during development phases where water stress was not intended. Experimental procedures are explained in Rossler et al. (2013) and Rossler (2014).

2.2. Crop productivity measurements

The degree of lodging within each plot was recorded by the same research technician using a visual rating that ranged from 1 to 9, where 1 = fully erect cane and 9 = completely lodged cane. In the Pongola experiments this occurred weekly from at least 3 months before harvest, while in the Komatipoort experiment lodge ratings were only recorded on three occasions, twice when daily inspection of the cane revealed that a lodging event occurred, and at harvest.

The first ratoon crops in field experiment 1 and 2 in Pongola was harvested on 20 May 2010 and 13 December 2011 respectively after a 4-week drying-off period. The first ratoon crop in the Komatipoort experiment was harvested on 19 March 2013, after a short (12 day) drying-off period.

Just prior to harvest a 12-stalk sample was collected from each plot for growth measurements (stalk length from base to natural breaking point, stalk fresh mass, stalk diameter and internode number) and to determine a range of milling quality characteristics, including estimated recoverable crystal percent (ERC %), which is an estimate of the recoverable value of sugarcane delivered to the sugar mill. The ERC % was calculated per stalk fresh weight (FW) as (equation 1):

$$\text{ERC}\ \% = aS - bN - cF \qquad (1)$$

where S = sucrose % per stalk FW; N= non-sucrose % per stalk FW (predominantly hexoses); F = fibre % per stalk FW and a, b, c are industry determined factors (0.978, 0.535, and 0.018 respectively) characterising the efficiency of sucrose extraction at the mill. The three components were estimated with near-infrared spectroscopy (NIR) with a Matrix-F NIR instrument (Bruker Pty. Ltd., South Africa) according to accepted industry protocol.

At harvest, the two centre cane rows in each plot were cut and bundled by hand and weighed using a hydraulic grab apparatus equipped with a load cell to determine cane yield (tons) per hectare (ha). The ERC yield (t/ha) per plot was subsequently estimated as (equation 2):

$$\text{ERC yield (t/ha)} = (\text{ERC \% x cane yield})/100 \qquad (2)$$

2.3. Crop modelling procedures

2.3.1. Description of lodging algorithm

The lodging algorithm, which was previously implemented in DSSAT-CanegroV4.5 and in Canesim models (Singels, 2007; Singels et al., 2008) aims to represent the following conceptual framework. It is presumed that two factors exert force on upright cane that can cause it to lodge. These are (1) the mass of the cane stalks and associated leaf material, plus the water retained on it, and (2) wind. Cane stalks are anchored in the soil and their ability to withstand these forces are dependent on cultivar characteristics as well as the wetness of the soil around the roots. The ability to withstand these forces also varies somewhat between stalks of the same crop, hence causing partial and incremental lodging as the crop increases mass and becomes progressively more susceptible to lodging. The modelling approach was to effectively reduce the mass threshold above which lodging occurs, on days when wind and wet soil were deemed to have contributed.

Partial or full lodging of cane stalks are simulated when the fresh mass of above-ground plant parts (AFM in t/ha) plus the rainfall and irrigation water retained on it (WM in t/ha), that is the aerial mass (AM in t/ha), exceeds a variety-specific threshold (AMbase in t/ha, the aerial mass at which lodging commences when other lodging factors such as water and wind are absent). The extent of lodging is proportional to the magnitude of the extent to which the threshold is exceeded. Full lodging is simulated when AM equals or exceeds an upper threshold (AMmax, the aerial mass at which a crop becomes fully lodged). This attempts to represent the variation in stalks' and/or stools' ability to withstand lodging that often results in partial lodging. In Eq. 3 to 7 the mathematical representation of these simulations are provided:

$$Flodge_{AM,i} = (AM_i – AMbase)/(AMrange) \quad (3)$$

$$AM_i = AFM_i + WM_i \quad (4)$$

$$AFM_i = ADM_i/DMC \quad (5)$$

$$WM_i = (Rint_i + Iint_i) \, . \, \rho \quad (6)$$

where $Flodge_{AM,i}$ is the fraction of cane stalks that can potentially lodge due to excessive aerial mass on day i, AMrange is the range in AM from the point where lodging commences up to the point where lodging is complete (recognizing the variability in stalks' ability to withstand lodging forces), ADM_i is the aerial dry mass of day i, DMC is the dry matter content of aerial dry mass (assumed to be 0.27), $Rint_i$ and $Iint_i$ is rainfall and overhead irrigation intercepted by the canopy on day i, and ρ is a coefficient for converting the units of intercepted water from mm (kg/m^2) to t/ha.

$Rint_i$ and $Iint_i$ is calculated by the Canesim model as a function of canopy cover, rainfall and/or overhead irrigation amount. A fully canopied crop (such as crops prone to lodging) will intercept all rainfall and/or overhead irrigation up to a maximum value of 2 mm per day (Schulze et al., 2008).

Lodging can be exacerbated by a water saturated top soil and by strong wind. The saturated soil effect is simulated by adding 0.25 to the lodged fraction ($Flodge_{SWC}$ = .25) when the available soil water content of the profile is at or above field capacity (TAM).

The lodged fraction also increases by 0.25 ($Flodge_{U}$ = 0.25) when daily windrun (U_i in km/d) exceeds a threshold (Ux) of 200 km/d. The combined extent of lodging due to all three factors is then calculated (Eq. 8):

$$Flodge_{P,i} = Flodge_{AM,i} + Flodge_{SWC,i} + Flodge_{U,i} \quad \text{with } 0 <= Flodge_{P,i} <= 1 \qquad (8)$$

where $Flodge_{P,i}$ is the potential extent of lodging on day i, expressed as a fraction of the stalks per unit area. Lodging is only simulated when the value of $Flodge_{P,i}$ exceeds the actual lodged fraction of the previous day ($Flodge_{i-1}$) (Eq. 9). The lodged fraction on the given day ($Flodge_i$) is then set equal to $Flodge_{P,i}$ and the actual extent of lodging on day i equals the difference between $Flodge_{P,i}$ and $Flodge_{i-1}$.

$$Flodge_i = Max\,(Flodge_{P,i}, Flodge_{i-1}) \qquad (9)$$

This enables the simulation of incremental lodging, as is often observed, with stronger forces required to lodge stalks that have remained upright during previous lodging events. Eq. 8 also implies that wind and a saturated top soil will only contribute to lodging (a maximum effect of 25% each) when the aerial mass is high enough to push the current value of Flodge over its previous highest value.

The model simulates the impact of lodged cane on the interception of radiation (FI) and on radiation use efficiency (RUE, here defined as the dry biomass assimilated through gross photosynthesis (before respiration), per unit intercepted shortwave radiation) as indicated in Eq. 10 and 11. Although the work by Singh et al. (2002) shows that different mechanisms are involved in yield reduction, ultimately biomass growth per unit intercepted radiation is reduced, as well as the amount of radiation intercepted. These two processes are the main drivers of simulated biomass accumulation and are reduced by 13 and 23% respectively for fully lodged cane based on results of two experiments conducted in Ayr (1998/99) and Feluga (1997/98), Australia (Singh et al., 2002). Partially lodged cane has a proportional impact.

$$RUE = RUEo \cdot (1 - Flodge \cdot \Delta RUE) \quad (10)$$

$$FI = FIo \cdot (1 - Flodge \cdot \Delta FI) \quad (11)$$

where RUEo is the unadjusted RUE of an erect crop, ΔRUE is the fractional reduction in RUE for a fully lodged crop, FIo is the unadjusted fractional interception of radiation for an erect crop and ΔFI is the reduction in FI for a fully lodged crop .

The simulated lodge rating (LRsim) was calculated from the lodged fraction (Flodge) as follows (Eq. 12):

$$LRsim = 8\ Flodge + 1 \quad (12)$$

This implies a range from 1 to 9 for LRsim, which corresponds to the scale of visual ratings of lodging.

2.3.2. Model calibration

The focus here was on evaluating the simulation of (1) the onset and extent of lodging as it progressed over time and (2) the impact of lodging on crop yields. Confounding effects caused by simulation errors from other aspects of the model had to be minimized to enable a meaningful evaluation of the lodging algorithm. It was therefore important to get simulated biomass at the time of lodging close to the actual values for a meaningful assessment of the lodging algorithm. This was achieved by forcing the Canesim model to produce simulated cane yields that were close to the measured yields of the control treatments, by adjusting RUEo values for each experiment. The adjusted RUEo values were then used to simulate all treatments of a given experiment.

The default parameters for the lodging algorithm, as used in the Canegro model (Singels et al., 2008), were used in initial runs (Table 1). These values resulted in simulated lodging occurring slightly too early for the N25 variety in the Pongola 1 experiment, and too late for the WW treatment (which had the largest extent of lodging) in the Komatipoort experiment, where N49 was used. This was rectified by increasing the value of AMbase to 230 t/ha for N25 and decreasing it to 200 t/ha for N49, reflecting a possible higher susceptibility to lodging of N49 compared to N25 (Table 1).

2.3.3. Model evaluation

Simulated values of the onset and extent of lodging were compared to observed values. Simulated and observed yield reduction was also compared where possible.

2.4. Statistical analysis

Variables were analysed using a one-sided Student's t-test. Variables were first tested for normality and homogeneity using the Shapiro-Wilk and Bartlett tests respectively (Genstat v.14). The accuracy of the simulated extent of lodging was quantified by the root mean square error (RMSE) between daily values of simulated and observed lodge rating (LRsim

Table 1

Description of model parameters.

Parameter	Description	Default value	Calibration
AMbase (t/ha)	Aerial dry mass at which lodging commences when other lodging factors such as water and wind are absent	220[1]	230 (N25) 200 (N49)
AMrange (t/ha)	Range in aerial dry mass required for complete lodging	30[1]	-
$Flodge_{SWCo}$	Maximum increase in lodging fraction due to a saturated soil	0.25[1]	
Ux (km/d)	Daily wind run above which lodging susceptibility is increased	200[1]	-
$Flodge_{Uo}$	Maximum increase in lodging fraction due to wind	0.25[1]	-
ΔRUE	Reduction in radiation use efficiency for a fully lodged crop	0.23[2]	-
ΔFI	Reduction in fractional interception of radiation	0.13[2]	-

for a fully lodged crop

[1] Singels et al. (2008); [2] Singh et al. (2002)

and LRobs) for the period from when simulated or observed lodging first commenced up to the date of harvest.

3. Results

3.1 Effects of lodging on crop productivity

3.1.1. Field experiment 1 (Pongola - crop on autumn harvest cycle)

Strong winds accompanied by rain 340 days after ratoon start (11 weeks before harvest) caused the onset of lodging in field experiment 1. Heavy rain in excess of 100 mm, accompanied by strong wind, resulted in severe and widespread lodging 13 days later within all the plots without bamboo scaffolding. The development and severity of lodging was monitored through frequent visual lodging ratings.

Despite these adverse weather events the bamboo scaffolding was highly effective in preventing lodging in the not-lodged control treatment. This enabled accurate quantification of the impact of lodging on various crop productivity parameters (Table 2). Cane yield in the lodged treatment (179.3 t/ha) was not significantly lower than in the not-lodged control treatment (195.9 t/ha) at harvest (Table 2). Stalk length (measured from base to natural breaking point) and stalk fresh mass (g/stalk) was respectively 10.3% and 20.3% lower ($p < 0.05$) in the lodged treatment, whereas stalk diameter was not affected. The stalks in the lodged treatment also had a lower number of internodes (9.1%) compared to the not-lodged control treatment ($p < 0.05$). Although these significant effects on an individual stalk basis did not translate into cane yield differences, they are good indicators of the diminished growth vigour induced by lodging.

Cane quality (ERC%) in the stalks of the lodged treatment (9.7%) was not significantly lower than in the not-lodged control treatment (11.1%). The occurrence of lodging resulted in a statistical significant ($p < 0.05$) lower ERC yield of 20.6% (4.5 t ha^{-1})

Table 2

Effects of lodging in field experiment 1 on selected yield components of variety N25 at harvest (415 days after crop start). Significant differences ($P < 0.05$) between treatment means are indicated by different uppercase letters. One-sided Student's t-test results for each yield component are provided. The percentage difference for each parameter in the lodged treatment relative to the not-lodged control is shown at the bottom of the table.

Treatment	**Stalk length (cm)**	**Stalk fresh mass (g/stalk)**	**Stalk diameter (mm)**	**Internodes (number/stalk)**	**ERC (%)**	**Cane yield (t/ha)**	**ERC yield (t/ha)**
Lodged	269^{a}	1233^{a}	27.8^{a}	20.8^{a}	9.7^{a}	179.3^{a}	17.3^{a}
Not-lodged	300^{b}	1548^{b}	28.0^{a}	22.9^{b}	11.1^{a}	195.9^{a}	21.8^{b}
t-test	*0.02*	*0.003*	*0.39*	*0.002*	*0.11*	*0.08*	*0.04*
% difference	-10.3	-20.3	-0.7	-9.1	-12.6	-8.4	-20.6

compared to the not-lodged control treatment (Table 2). The lower ERC yield in the lodged treatment could be ascribed to the dual, albeit statistically non-significant ($p > 0.05$), lower cane yield and ERC% values (Table 2).

3.1.2. Field experiment 2 (Pongola - crop on summer harvest cycle)

The first signs of lodging in field experiment 2 were observed 310 days after ratoon start. During the remainder of the crop cycle lodging gradually progressed, but never reached the same severity as observed in field experiment 1.

The bamboo scaffolding was again highly effective in preventing lodging in the not-lodged control treatment. This enabled comparative quantification of the impact of lodging on the same set of crop productivity parameters as measured in experiment 1, but in a situation where only moderate lodging occurred 10 weeks prior to harvest (Table 3).

Similar to field experiment 1, cane yield in the lodged treatment (146.8 t/ha) was not significantly ($p > 0.05$) lower than in the not-lodged control treatment (158.4 t/ha). However, the 7.3% difference in cane yield was supported by a reduction in stalk length, which was 14% lower ($p < 0.05$) in the lodged than not-lodged control treatment, indicating reduced growth vigour on a per stalk basis (Table 3). Contrary to experiment 1, none of the other stalk growth indicators were significantly affected by lodging.

Similar to experiment 1, ERC% in the stalks of the lodged treatment (13.4%) was not significantly different from the not-lodged control treatment (13.6%). Contrary to experiment 1, prevention of lodging did not result in a statistical significant difference in ERC yield between the two treatments (Table 3).

Table 3

Effects of lodging in field experiment 2 on selected yield components of variety N25 at harvest (383 days after crop start). Significant differences ($P < 0.05$) between treatment means are indicated by different uppercase letters. One-sided Student's t-test results for each yield component are provided. The percentage difference for each parameter in the lodged treatment relative to the not-lodged control is shown at the bottom of the table.

Treatment	**Stalk length (cm)**	**Stalk fresh mass (g/stalk)**	**Stalk diameter (mm)**	**Internodes (number/stalk)**	**ERC (%)**	**Cane yield (t/ha)**	**ERC yield (t/ha)**
Lodged	208[a]	1011[a]	23.5[a]	22[a]	13.4[a]	146.8[a]	19.7[a]
Not-lodged	242[b]	1094[a]	22.7[a]	21.5[a]	13.6[a]	158.4[a]	21.6[a]
t-test	*0.001*	*0.17*	*0.3*	*0.31*	*0.33*	*0.14*	*0.13*
% difference	-14	-7.6	+3.5	+2.3	-1.5	-7.3	-8.8

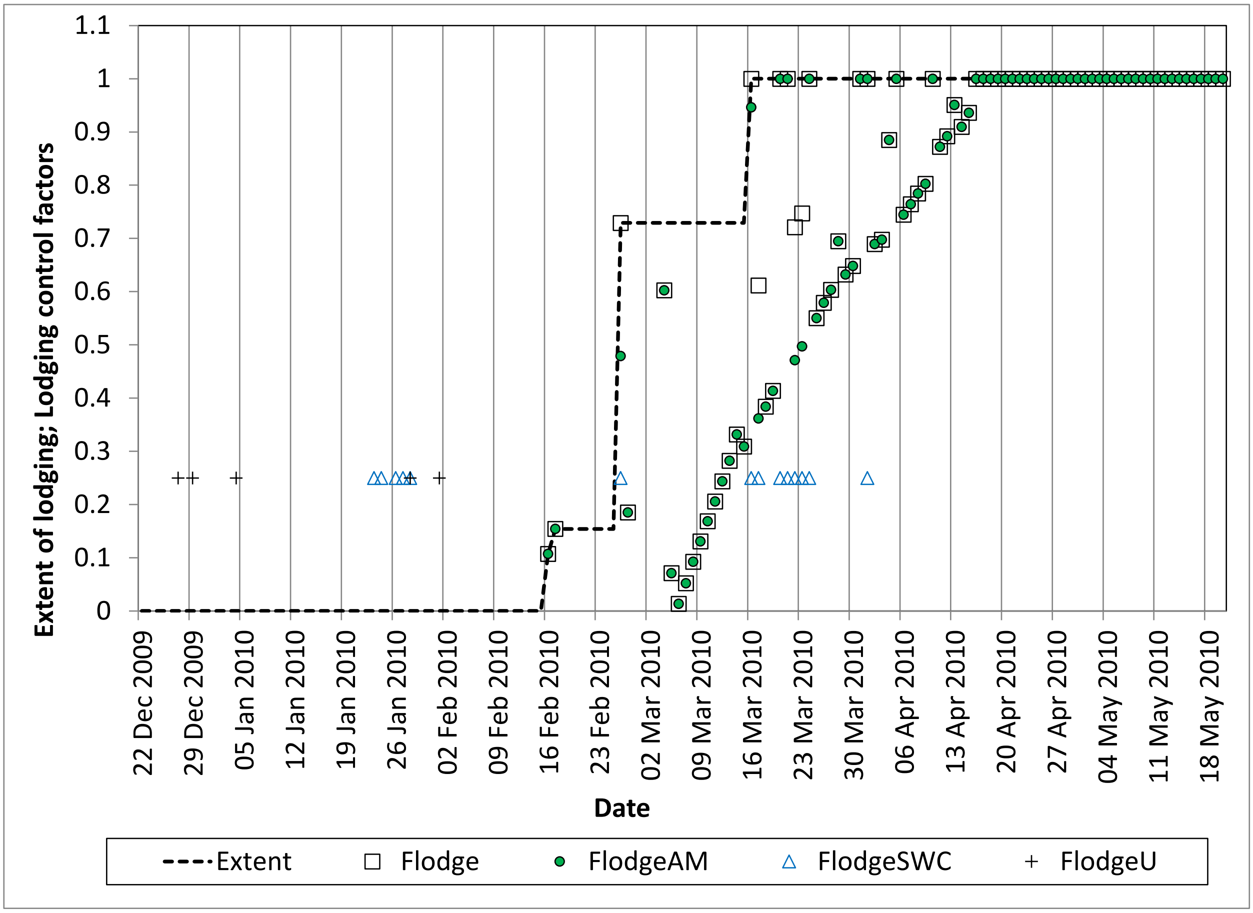
3.1.3. Komatipoort field experiment

The WW treatment achieved the highest observed cane yield (148 t/ha) followed by the T (140 t/ha), SE (136 t/ha) and T+SE (130 t/ha) treatments (Table 4). The differences in yield, although not statistically significant, can be related to the extent and timing of water stress imposed in the different treatments (see Rossler, 2014 for a full explanation). This also led to different lodging patterns for the different treatments. The WW, T and SE treatments first lodged on 4 February 2013, although the extent of lodging differed in proportion to the size of the crop (WW>T>SE, Table 4). The T+SE treatment, which experienced the most water stress and had the lowest yield of all the treatments, first lodged on 7 March 2013 and at harvest only about 17% of stalks were lodged, compared to about 96% in the WW and T treatments and 42% in the SE treatment. As mentioned previously the data collected in this experiment were considered useful for model testing (see section 3.2 below) because of the differences in lodging onset and severity that was introduced through the various water stress treatments within the same field.

3.2 Modelling of lodging onset and impacts on yield

Figure 1 shows the progression over time of key lodging control factors used in the calculation of the extent of lodging (Eq. 9) for the lodged treatment in the first field experiment at Pongola (Pongola 1). The example illustrates how the aerial mass control factor ($Flodge_{AM}$, solid circles) increases steadily over time due to the increase in dry biomass of the crop and how it spikes upward on rainy days when intercepted rainfall adds to the mass. The first exceedance of aerial mass above the threshold value occurred on 16 and 17 February 2010, causing limited extent of lodging with $Flodge_{AM}$ reaching a value of 0.15. The second simulated lodging event took place on 26 February 2010, when the rainfall added to the aerial mass control factor ($Flodge_{AM}$ = 0.48). In this case, a wet soil ($Flodge_{SWC}$ = 0.25,

Figure 1 : Simulated extent of lodging for the lodged treatment of the Pongola1 experiment, and the control factors driving lodging: wind (FlodgeU), soil water content (FlodgeSWC), aerial mass (FlodgeAM) and the combined effect (Flodge) (see Eq. (8)). All parameters are expressed in fractions.



open triangles) contributed further, adding to the value of the combined lodging control factor (Flodge = 0.73, open squares), implying that 73% of stalks were now lodged. A third lodging event was simulated on 16 March, caused by a heavy crop with intercepted rainfall adding to its mass ($Flodge_{AM}$ = 0.94), and a wet soil ($Flodge_{SWC}$ = 0.25), implying 100% lodging (Flodge=1.0). The full extent of simulated lodging over time is indicated by the black dashed line. In this example wind (FlodgeU, crosses) did not play a role, with only a few cases of strong winds when the crop was not prone to lodging due to low aerial mass (e.g. on 29 December 2009 and 4 January 2010). Before the 16^{th} of February 2010, there were also a number of instances of wet soil ($Flodge_{SWC}$ = 0.25, open triangles), but because of low aerial mass, the crop was not prone to lodging yet.

Modelling results are summarized in Table 4. RUEo had to be increased for all the experiments, and substantially so for the Pongola1 and Komatipoort experiments, in order to match simulated cane yield with observed values for control treatments. There are many possible causes for these exceptionally high cane yields. Actual interception of radiation could have been higher than simulated due to quicker canopy development. Conversion of intercepted radiation to biomass accumulation could have been higher than simulated because of genetic and environmental factors not accounted for adequately by the model. The partitioning of biomass to stalks could have been higher than simulated. Differences in simulated and observed cane yields can also partly be ascribed to actual stalk moisture contents exceeding simulated moisture contents. The data available from the study were unfortunately inadequate to investigate the exact causes of the apparently high RUEo values. The study focused on testing the lodging aspect of the crop only, and was not concerned with how some of the crops succeeded in achieving the high yields.

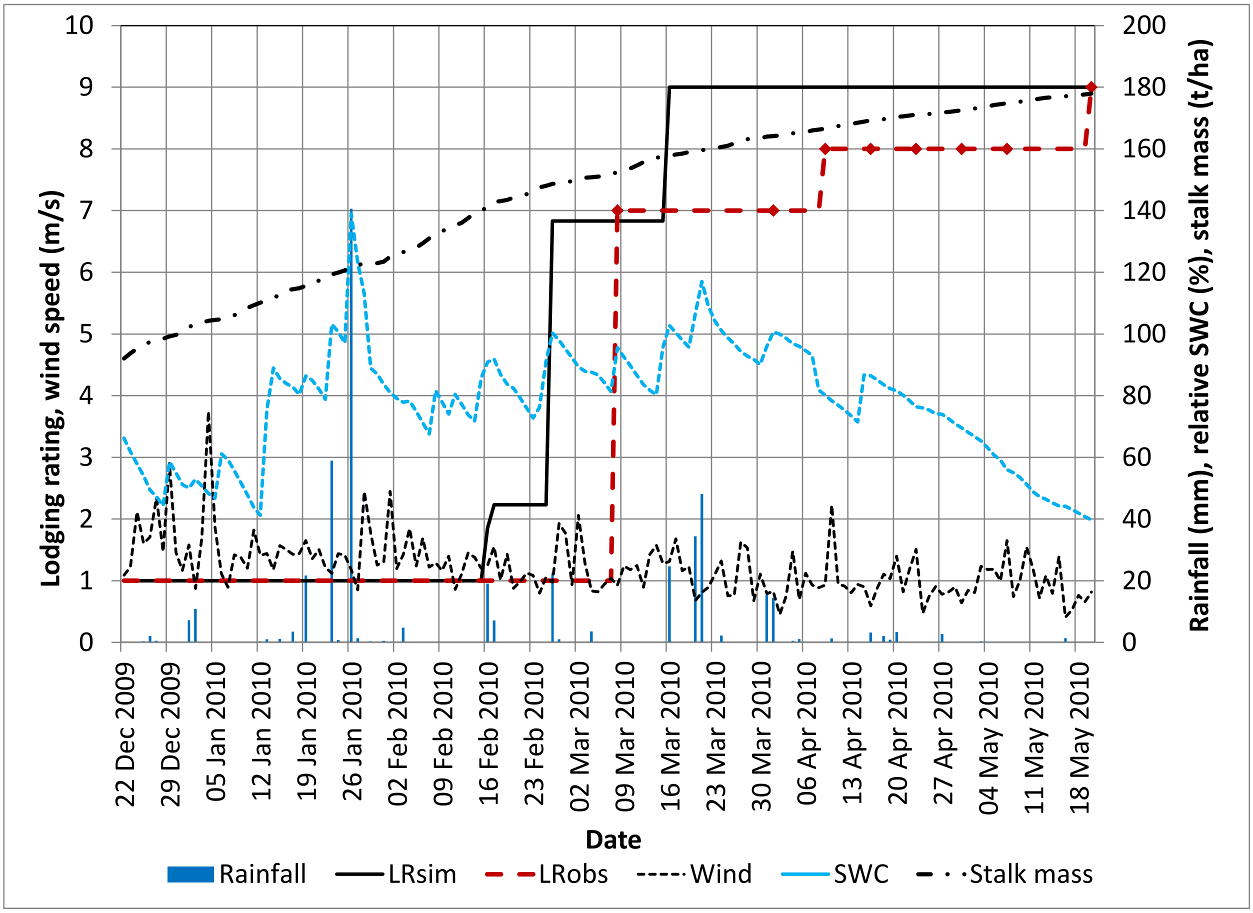
Table 4

Simulated (Sim) and observed (Obs) onset and extent of lodging, the accuracy of lodging predictions (root mean square error - RMSE), and impact of lodging on cane yields for the different treatments in the first (Pongola1) and second (Pongola2) experiments conducted in Pongola and the experiment in Komatipoort (from Rossler, 2014). The radiation use efficiency (RUEo) values used for crop simulations (while crops were erect) are also given.

Experiment	**Treatment**	**RUEo (g/MJ)**	**Onset of lodging**			**Lodge rating at harvest**		**Lodge rating RMSE**	**Cane yield (t/ha)**	
			Obs (date)	**Sim (date)**	**Difference (days)**	**Obs**	**Sim**		**Obs**	**Sim**
Pongola 1	Not-lodged	2.80	-	-	-	-	-		196	196
Pongola1	Lodged	2.80	08-Mar-10	16-Feb-10	-20	9.0	9.0	2.32	179	180
Pongola 2	Not-lodged	1.90	-	-	-	-	-		158	159
Pongola2	Lodged	1.90	04-Nov-11	30-Oct-11	-5	6.0	6.7	1.01	147	156
Komati	T	2.60	04-Feb-13	11-Feb-13	7	8.8	9.0	2.77	140	145
Komati	SE	2.60	04-Feb-13	03-Feb-13	-1	4.4	7.9	3.15	136	134
Komati	T+SE	2.60	07-Mar-13	20-Feb-13	-15	2.4	4.8	2.12	130	130

Komati	WW	2.60	04-Feb-13	30-Jan-13	-5	8.7	9.0	2.70	148	147

Figure 2 : Simulated and observed lodging rating (LRsim and LRobs), daily average wind speed, available soil water content (SWC, expressed as percentage of the capacity) and simulated stalk mass for the last 5 months of the growing season for the Pongola1 experiment.



The onset of lodging was simulated reasonably well for most of the crops, while the extent of lodging at harvest was simulated very accurately for all crops (Table 4). The overall RMSE of simulated lodge ratings was 2.43.

For field experiment 1 at Pongola (Pongola1) two minor (16 and 17 February 2010) and one major (26 February 2010) lodging events were simulated (caused by a large crop saturated with rainfall) before actual lodging was first observed on 8 March 2010 (Fig. 2 and Table 4). For field experiment 2 at Pongola (Pongola2) the simulated and observed onset of lodging was much closer, with observed lodging occurring only 5 days after the simulated lodging date (Fig. 3 and Table 4). The model was also successful in mimicking the gradual stepwise progression of lodging that was observed in this experiment (relatively low RMSE values in Table 4), while the final extent of lodging was predicted accurately.

Cane in the WW treatment of the Komatipoort experiment lodged heavily on 4 February 2013, with a 2nd minor event on 7 March 2013 (Fig. 4). Simulated lodging first occurred 31 January 2013, followed by a second event on 4 February 2013. The extent of lodging was underestimated at this stage. Simulated lodging continued in a stepwise manner as aerial mass increased, and rainfall wetted the soil (reducing its anchoring ability) and the crop (increasing the aerial mass). The simulated crop became fully lodged on 1 March 2013. The extent of lodging at harvest was accurately simulated (Fig. 4 and Table 4).

For the T treatment simulated lodging occurred 7 days later than observed (results not shown), and the extent of lodging at harvest was very close to that observed (Table 4).

Much less lodging occurred in the SE and T+SE treatments because the aerial mass of the crops was lower and the soil water contents were lower than that of the WW and T treatments due to more stress imposed by deficit irrigation. The simulated onset of lodging was 6 days late for the SE treatment and about three weeks too soon for the T+SE treatment

Figure 3 : Simulated and observed lodging rating (LRsim and LRobs), daily average wind speed, available soil water content (SWC, expressed as percentage of the capacity) and simulated stalk mass for the last five months of the growing season for the Pongola2 experiment.

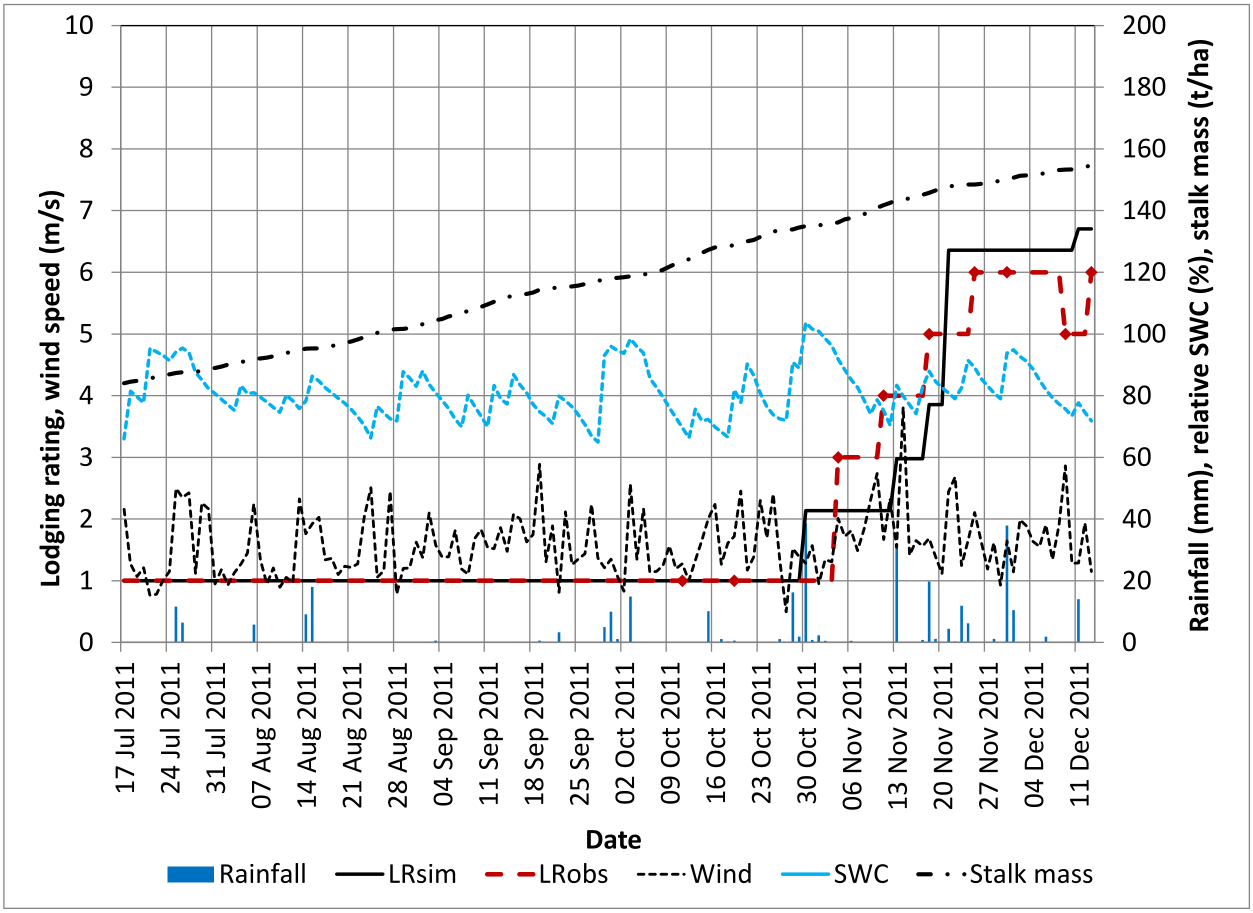


Figure 4 : Simulated and observed lodge rating (LRsim and LRobs), daily average wind speed, available soil water content (SWC, expressed as percentage of the capacity) and simulated stalk mass for the last five months of the growing season for the WW treatment in the Komatipoort experiment.

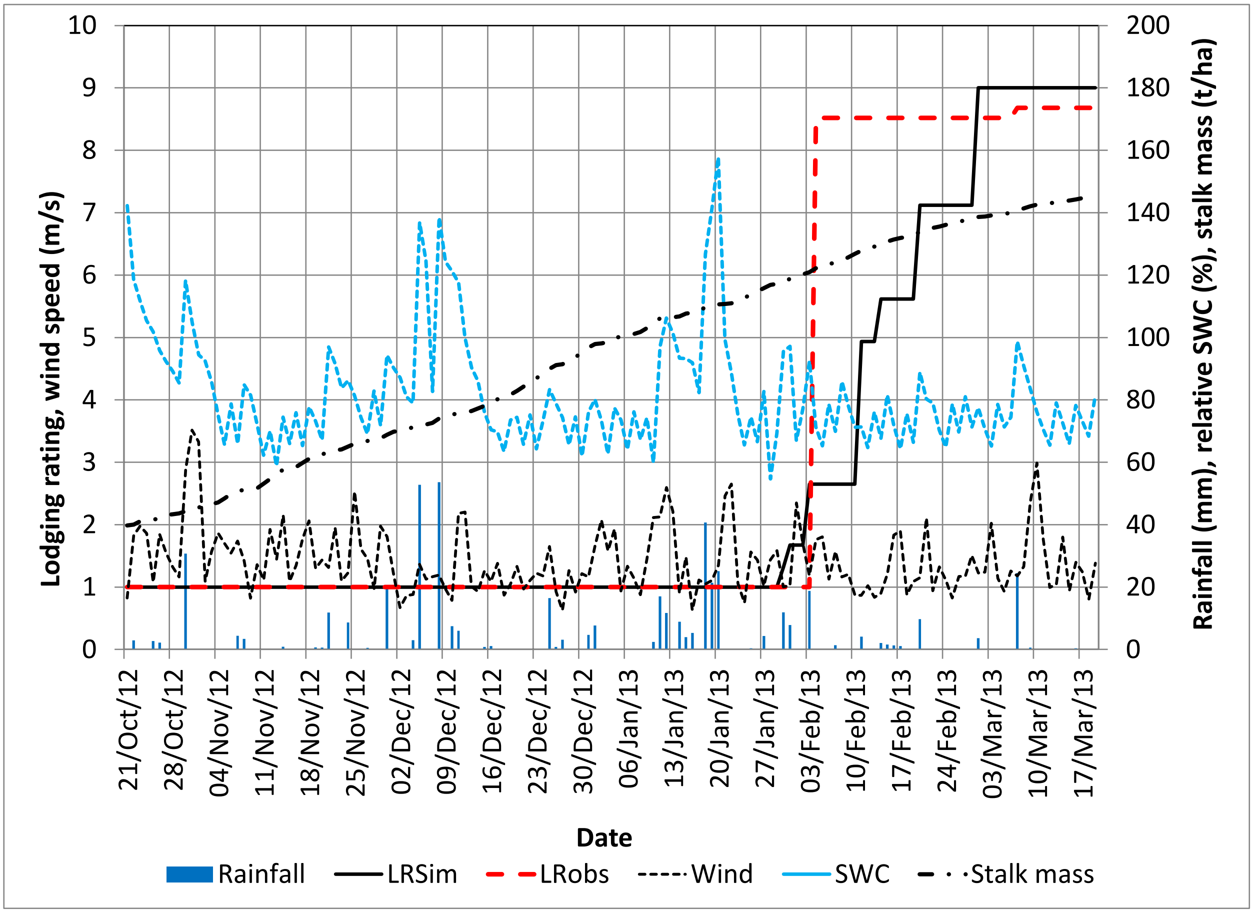
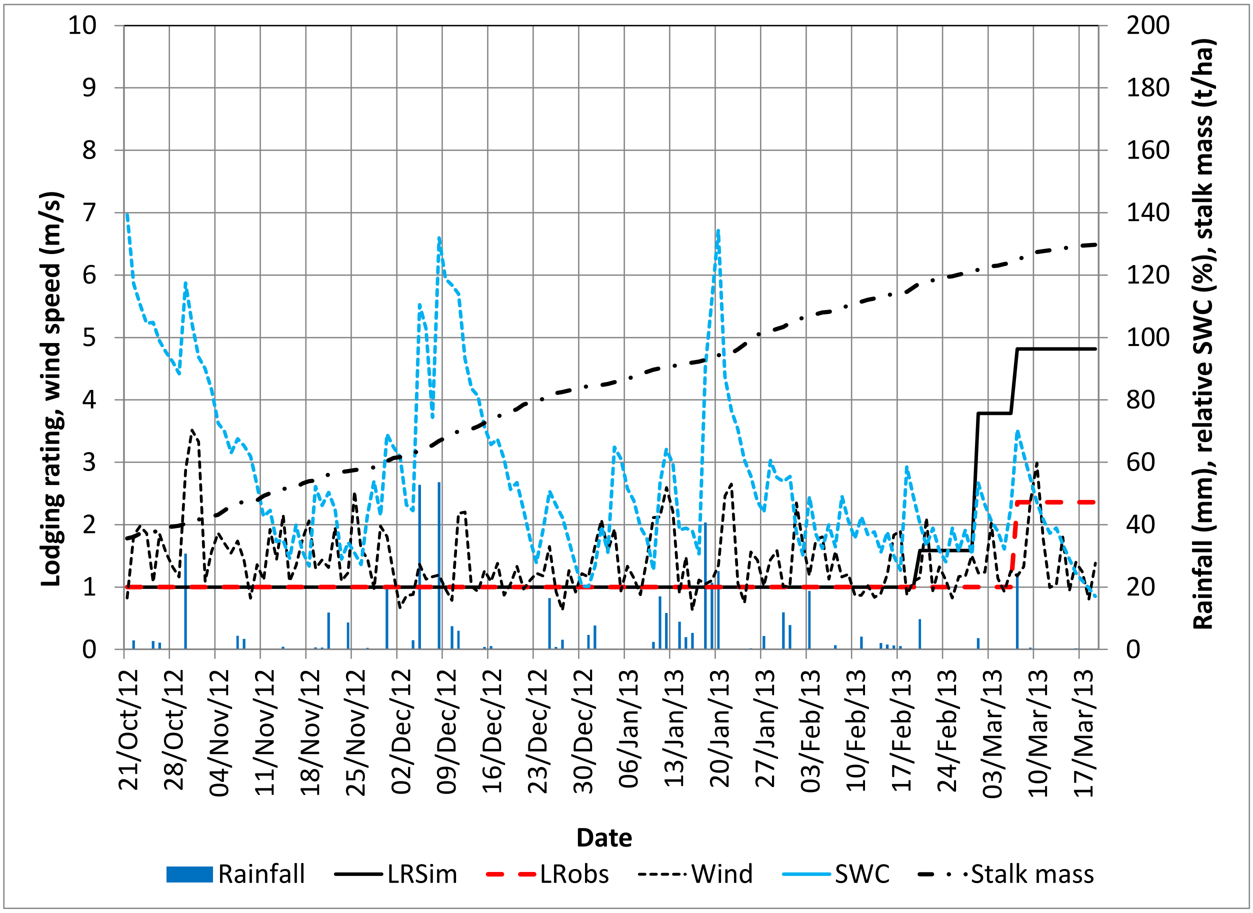


Figure 5 : Simulated and observed lodging rating (LRsim and LRobs), daily average wind speed, available soil water content (SWC, expressed as percentage of the capacity) and simulated stalk mass for the last five months of the growing season for the T + SE treatment in the Komatipoort experiment.



(Fig. 5 and Table 4), while the simulated extent of lodging was overestimated in both cases (relatively high RMSE values in Table 4).

The impact of lodging was simulated reasonably well for the Pongola1 crop (9.5% simulated vs 8.4% observed reduction in cane yield) and was underestimated somewhat in the Pongola 2 crop (2.5% simulated vs 7.3% observed reduction in cane yield) (Table 4). Results suggest that the ΔRUE and ΔFI parameter values are appropriate. It was not possible to evaluate the simulation of lodging impacts in the Komati experiment because treatments experienced different water regimes and there was not a control treatment for comparison.

4. Discussion

The results of the two field experiments conducted at Pongola under typical South African sugarcane growing conditions revealed that when severe lodging occurs 10 – 11 weeks prior to harvest, ERC yield may be reduced by as much as 20.6%. However, in the case of only moderate lodging 10 – 11 weeks prior to harvest, no significant effect on ERC yield was observed. In both experiments reduced growth vigour in the lodged treatment was supported by significant reductions in stalk length compared to the not-lodged control treatment. Reductions in stalk length did however not translate into significantly lower cane yields due to large variability between plots. It must be noted that manual harvesting, and accurate weight determination of severely lodged sugarcane, is extremely difficult, hence the significant effects on individual stalk length but not on cane yield. Above results compare well with results from Australia where prevention of severe lodging resulted in 15 – 35% higher sugar yields (Singh et al., 2002).

The modeling exercise showed that the onset, progression and final extent of lodging was simulated realistically for various soil/crop/atmospheric conditions when crop biomass simulations were forced to reflect actual values. Very little parameter calibration was required – the threshold for the commencement of lodging was increased for variety N25, and reduced for variety N49, suggesting that the latter was more prone to lodging than variety N25. The model predicted the onset and extent of lodging reasonable well for most treatments, except for the SE treatment of the Komati experiment where the extent of lodging was overestimated. Simulated lodging was primarily driven by crop size and lodging events were triggered by rainfall that added weight to the aerial mass of the crop, and reduced the anchoring ability of the soil through saturation of the top soil. The contribution of wind and a wet top soil to crop lodging could not be tested directly and future testing with appropriate data is advised.

The simulation study also highlighted the fact that variety tolerance/sensitivity to lodging should be assessed in the context of crop size. This implies that crop aerial mass (or at least cane yield) should also be estimated/recorded when the extent of lodging is rated. Existing variety trial data could possibly be interrogated to generate this information, which is needed for accurate simulation of lodging and its impacts.

This is the first report of its kind where an integrated experimental and modeling approach was followed to enhance our understanding and simulation ability of lodging in sugarcane. More accurate simulation of lodging and its impacts on yield will obviously improve the accuracy of yield predictions by crop models. This will increase the reliability and relevance of various model applications such as crop forecasting, climate change impacts, and exploring crop improvement and crop management options. For example, the performance of genotypes with different susceptibility levels to lodging can be simulated, to assist in identifying the optimal range for a given environment. The economic impact of lodging and of possible control measures, such as manipulating early growth through withholding irrigation can also be calculated if the extent of lodging and its impact on cane yield can be predicted.

Acknowledgements

The authors acknowledge the technical assistance with the field experiments provided by members of the SASRI technical team at Pongola and Komatipoort. Special thanks to Professor Martin Steyn (Department of Plant Production and Soil Science, University of Pretoria, South Africa) and Mr. Francois Olivier (South African Sugarcane Research Institute) for provision of student supervision to Mr. Ryan Rossler. Funding of this research by the South African Sugarcane Research Institute is acknowledged.

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Highlights

- Lodging in irrigated sugarcane resulted in decreased sugar yields of up to 21%
- An algorithm for simulating lodging onset, extent and yield impact was tested
- The onset and extent of lodging were simulated realistically
- More accurate simulation of lodging will improve yield predictions by sugarcane models