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Using crop fall patterns to provide an insight into thunderstorm downbursts

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SUMMARY
The aim of this research is to investigate whether crop fall patterns due to thunderstorm downburst-like events can provide an insight into the flow structure of a downburst. Crop failure was simulated using an analytical model of the three-dimensional velocity flow field coupled with a generalised plant model. Using this approach, the concept of the lodging front was established - a dimensionless variable used to quantify the spatial extent of crop failure. It is shown that the crop failure results in a diverging pattern where the angles at which the crops fall depends on their relative location on the lodging front. Comparison with full-scale data suggests that the current model is capable of predicting realistic crop fall patterns well and could potentially be used in the future to assess the strength of downbursts.

Keywords: crop fall pattern, thunderstorm downburst, crop failure

1. INTRODUCTION

Interest in the impact of tornadoes and thunderstorm downbursts continue to grow within the wind engineering community. As these types of transient winds are complex, the community is still considering how best they can be addressed in the design process. Numerous studies have been conducted to physically simulate (Babaei et al., 2021; Jesson et al., 2015; Romanic and Hangan, 2020) and numerically model (Aboshosha et al., 2015; Kim and Hangan, 2007; Li et al., 2012) such events. However, due to the complexity of geometric, kinematic and dynamic scaling that must be achieved, it is often difficult to compare the results between different simulations and full-scale measurements, and thus meaningfully extrapolate the findings for the purposes of design. Additionally, as downbursts tend to be highly localised in both space and time, there is a lack of comprehensive full-scale data. As a result, the wind fields associated with downburst-like events are relatively poorly understood. Hence, this work aims to provide an insight into the flow field of a downburst-like event and explore the crop fall patterns that may arise from such winds.

2. CROP MODELLING

The generalised crop fall model (equation (1)) used in this study was developed by Baker et al. (2014). The crops are modelled as a series of inextensible cantilevers with a wind load applied at the free end. The fixed end of the cantilever represents the plant's foundations. By applying Newton's second law at the free end, the expression for the bending moment at any point along the stem can be derived. The resultant moment is then compared to the plant's capability to resist bending, which is represented by two separate failure models – the first model accounts for stem resistance with the second model representing the plant's anchorage. When the applied bending moment due to the wind is equal to or exceeds the plant's failure moment, crop fall, or lodging occurs. Experience has shown that root failure occurs over a relative long time period (i.e., it is associated with fatigue of the plant's roots and surrounding soil). Hence, it what follows only stem failure associated with a short-term wind gust is considered.

$$\Omega_l = \left(\frac{\omega_n^2 (z_c/g)(\sigma\pi a^3/4)\left(1-((a-t)/a)^4\right)}{\left(1+\omega_n^2(X/g)\right)(0.5\rho A C_F)}\right)^{0.5} \quad (1)$$

3. DOWNBURST WIND FIELD MODELLING

Whilst it is acknowledged that the transient nature of a downburst flow field is complex and varies both in time and space, the model developed assumes that crop failure occurs quickly and as such, such variations can be neglected. The downburst wind field is represented by a radial component of velocity (U) and a vertical component velocity (W). In what follows, both U and W are normalised by the maximum component of radial velocity (U_m) and denoted by the use of an overbar, i.e., $\bar{U} = U/U_m$ and $\bar{W} = W/U_m$. The normalised radial velocity is expressed as a function of normalised radial distance ($\bar{r}$) from the centre of the impingement and normalised vertical distance ($\bar{z}$) above ground as:

$$\bar{U} = \frac{2\bar{r}}{(1+\bar{r}^2)} \frac{4\bar{z}}{(3+\bar{z}^4)} \quad (2)$$

where $\bar{r} = r/r_m$ and $\bar{z} = z/z_m$. r_m and z_m represents the radial distance and vertical distance corresponding to U_m respectively. The vertical velocity is derived from the radial continuity equation and the ratio between z_{max} and r_{max} is denoted by δ:

$$\bar{W} = -\frac{8\delta}{(1+\bar{r}^2)^2} \frac{\pi}{2\sqrt{3}} \quad (3)$$

4. CROP FALL PATTERN DUE TO DOWNBURSTS

4.1. Calculation of Lodging patterns

This work primarily focuses on the wind conditions near ground level at a height equivalent to the crop's centre of gravity (z_c), where the downburst vertical flow component is small. The normalised lodging velocity can therefore be expressed as the resultant wind speed, which is the vector sum of the radial velocity and the normalised translational velocity ($\bar{Q}$) of the downburst, expressed as:

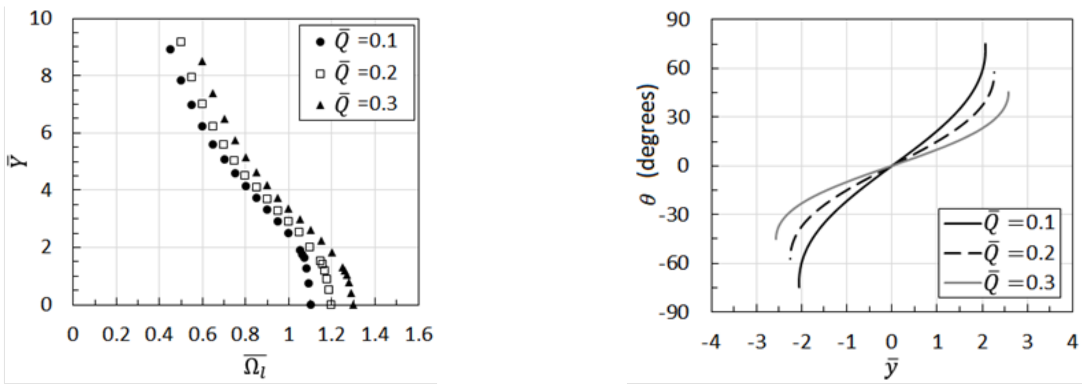
$$\bar{\Omega}_l^{\,2} = \left(\frac{\Omega_l}{U_{mc}}\right)^2 = \bar{Q}^2 + 2\bar{Q}\bar{U}_c cos\alpha + \bar{U}_c^{\,2} = \bar{Q}^2 + 2\bar{Q}\frac{2\bar{x}}{(1+\bar{r}^2)} + \left(\frac{2\bar{r}}{(1+\bar{r}^2)}\right)^2 \quad (4)$$

where Ω_l is velocity at which the crop fails, U_{mc} is the maximum value of the radial velocity at crop height, $\bar{Q} = Q/U_m$ with Q representing the downburst translation speed, x is distance from downburst centre in direction of storm translation and α wind angle relative to x axis. The crop fall direction (θ) relative to the x axis is given by:

$$\theta = tan^{-1}\left(\frac{\bar{U}_c sin\alpha}{\bar{Q}+\bar{U}_c cos\alpha}\right) \quad (5)$$

Thus, for values of $\bar{\Omega}_l$ below 1.0, the lodging velocity is less than the maximum velocity at crop's centre of gravity in the downburst and thus the downburst alone will cause the crop to lodge. For values above 1.0, the crop will only lodge when there is an added translational velocity of sufficient magnitude. The lodging process as a downburst passes over a crop can be assessed by numerically calculating equation (4) in terms of x and y. The region where the overall velocity first exceeds the crop lodging velocity can be quantified by use of a dimensionless parameter, the lodging width, the distance over which the downburst velocity exceeds the lodging velocity and thus over which lodging occurs.

Figure 1(a) shows the normalised distance from downburst centre normal to direction of storm translation (the 'lodging width') against the normalised crop lodging velocity. As illustrated in figure 1 (a), the lodging width falls as lodging velocity increases, i.e., as the crop becomes stronger, but increases as the translational velocity increases. Additionally, a diverging pattern of crop fall is observed when a downburst passes over a crop (figure 1 (b)) which is dependent on the translational speed of the downburst.



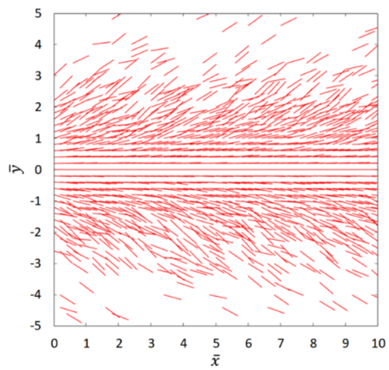
(a) (b)

Figure 1. (a) Variation of the lodging width with $\overline{\Omega}_l$ and $\bar{Q}$ (b) Variation of lodging angle across the lodging front.

4.2. The effect of crop variability

The effects of lodging speed and crop fall patterns were further examined by constructing a crop domain of 1000m x 1000m square, with randomly generated normalised lodging velocities. These lodging velocities where obtained using representative probability density functions corresponding to previously measured plant parameters (Berry et al., 2021). In what follows, it is assumed that a downburst passes along the centre line of the field with a normalised translational velocity $\bar{Q}$ of 0.2. This enables the crop fall angle in the crop domain to be generated as shown in figure 2(a).

In figure 2(b), the aerial photographs of a crop fall event at Eden-Walsh (Ontario, Canada) on 12/09/21 caused by downbursts is shown with an estimation of crop fall directions are indicated by red lines. A clear divergent crop fall pattern in the lower half of the photograph can be observed, while a more chaotic lodging pattern occurs in the top half of the photograph. Whilst further research is required, the initial results of the approach are encouraging.



(a)

(b)

Figure 2. (a) Vector plot of cropfall directions for a standard deviation of lodging velocity of 20% of the mean (b) Observed crop fall pattern at Eden-Walsh (80.3878 W, 42.7244 N, area 198 x 132 m).

5. CONCLUSIONS

This work has derived and integrated a novel model capable of representing the near ground wind fields with an existing crop model in order to examine possible crop fall patterns due to downburst-like event. The following conclusions were made:

- The three components of the velocity field of a downburst-like event can be represented using a relatively simple model which satisfies the continuity equation.
- Crop fall due to downbursts was shown to result in a diverging flow pattern, where the region of crop failure is a function of the local wind speed and downburst translation speed. Additionally, the angles at which the crops fall depend on their relative location on the lodging front.
- By using the model in conjunction with full-scale data, it is possible to calculate a range of downburst parameters which resulted in the observed failure, thus suggesting that the model has utility.

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Photograph used in figure 2(b) were kindly provided by Greg Kopp and Aaron Jaffe from University of Western Ontario and were recorded as part of the Northern Tornadoes Project. Their help is gratefully acknowledged.

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