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Crop lodging induced by wind and rain

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ABSTRACT

A methodology to estimate wind and rain effects on the four main growth crops in the United Kingdom is presented. The method is based on simulated weather scenarios acting on synthetic plants over a period of thirty years. The environmental data is generated with the UKCP09 Weather Generator considering future climate scenarios whereas plants are modelled as simple oscillators characterised by their mass, stiffness and damping. The joint probability of occurrence of wind and rain are estimated together with the conditions in which lodging would occur. The paper shows that the dynamic response of plants varies with season being the first three months of the year the most critical whilst the plants' performances define crop failure velocities ranging between 4 ms^{-1} and 23 ms^{-1} and associated failure rates of 50% and 5% per unitary velocity.

1. Introduction

The interaction of plants with the wind and the nature of plant failures which can occur during periods of high winds have been much investigated in the past. In Wright (1965) it was noticed that the characteristics of the flow through a canopy varied within the crop height and hence some parameterisation of the observed variation was proposed. Baines (1972), Denmead and Bradley (1967), Finnigan and Mulheran (1978), and Cionoco (1972) also discussed the nature of turbulence within canopies and provided additional insight of the flow dynamics that govern the energy flow exchange in canopies. A review of the interaction of plants with the wind can also be found in de Langre (2008). In terms of plant's modelling, Sellier et al. (2006) investigate the oscillation of trees via numerical modelling whilst Rodriguez et al. (2009) carried out experimental work to determine natural frequencies of walnut trees. For isolated plants the work of Baker (Baker, 1995; Baker et al., 1998; Sterling et al., 2003; Berry et al., 2003; Saunderson et al., 1999, 2000) is notable. Baker (1995) assumed that wheat plants and isolated trees could be idealised as two simple masses connected by a light inextensible element. The first mass represented the root-soil structure of the plant while the second represented the mass of the plant. Baker's model enabled the maximum wind induced base bending moment to be obtained which seemed reasonable when compared to the natural variations which can occur in the plant properties (e.g. stem diameter, root plate spread etc.). More recently, Martinez-Vazquez and Sterling (2011) showed that the model proposed in Baker (1995) can in fact be used to calculate lodging for large populations of plants. The present investigation builds on previous research and attempts to merge mechanical modelling techniques for plants with statistical predictions of environmental variables to calculate crop's behaviour. Environmental variables are simulated by the UKCP09 Weather Generator. This is a virtual facility that enables constructing future climate scenarios from where rain and wind conditions can be determined. In this investigation wind and rain scenarios are used to test plant crops in order to observe conditions that induce their failure. Four types of plants are considered, these are oats, wheat, barley, and rapeseed. The similarities and differences amongst the various plant responses are compared and discussed throughout.

The paper is organised as follows. Section 2 outlines the characteristics of the weather generator and its prediction capabilities; Section 3 provides the details of how to generate wind and rain databases based on the prediction tool; Section 4 describes how the wind turbulence within a canopy was modelled; Section 5 details the generation of synthetic plants, taking oats as a case study; Section 6 explains how to estimate the plant's resistance for the use of Baker's simplified model; Section 7 give full results of the response of oat crops subject to wind and rain; Section 8 extends the plant response analysis to the other plant types, whilst Section 9 provides some final remarks.

2. The UKCP09 weather generator

In recent years the Met Office Hadley Centre in collaboration with UK Climate impacts Programme and over thirty other organisations have developed the UKCP09 Weather Generator aiming at

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Table 1
Peak values of environmental parameters (q_{param}) related to the reference evapotranspiration.

T (°C)	e_d kPa	e_a kPa	R_n MJm^{-2}day^{-1}	U_2 (ms^{-1}) Eq. (2)	U_2 (ms^{-1}) Full-scale
18.04	1.52	2.01	11.56	3.85	3.5

visualising future climate fluctuations across the United Kingdom. This facility is capable to provide weather scenarios and associated measures of uncertainty until 2080. In the present research this tool was used to determine the most probable combinations of wind and rain that are likely to occur on the region of Cardington, UK (52.1055°N, 0.4244°W 29 m above MSL) and to evaluate their combined effect on oat crops.

The UKCP09 user's interface provides access to customised outputs that reflect the underlying UKCP09 climate projections. Pre-prepared maps and graphs can be used to select any land or marine region—defined by 5 km^2, within the UK. The available data includes 17 variables over land areas and 4 over marine regions. The following are the weather parameters over land areas that can be generated by using the referred tool (Jenkins et al., 2009).

- Mean temperature (°C)
- Mean daily maximum temperature (°C)
- Mean daily minimum temperature (°C)
- 99th percentile of daily maximum temperature in a season (warmest day of the season) (°C)
- 1st percentile of daily maximum temperature in a season (coolest day of the season) (°C)
- 99th percentile of daily minimum temperature in a season (warmest night of the season) (°C)
- 1st percentile of daily minimum temperature in a season (coldest day of the season) (°C)
- Precipitation rate (mm/day)
- 99th percentile of daily precipitation rate in the season (wettest day of the season) (mm/day)
- Specific humidity (%)
- Relative humidity (%)
- Total cloud (%)
- Net surface long wave flux (W/m^2)
- Net surface short wave flux (W/m^2)
- Total downward short wave flux (W/m^2)
- Mean sea level pressure (hPa)
- Grass reference evapotranspiration (mm/day)

Environmental data for any selected region are accessed by setting up a request to the UKCP09 central unit, for example by following the procedure given in Appendix A. After the request is made the simulated data is made available for the user to download.

3. Hourly rain and wind database

The amount of rain per day and per hour is directly available from the output of the UKCP09 simulator but not for the velocity of the wind. In such case one can estimate the hourly wind regime through a two-step process namely (i) inferring the daily winds by using the grass reference evapotranspiration parameter (only available on a daily basis) and (ii) downscaling the data to estimate hourly winds. The way this process was applied for this research is described in the following paragraphs.

3.1. Daily wind

There are a number of methods to infer the wind from the environmental parameters such as those discussed in Ventura et al. (1999), Allen et al. (1994), Ekström et al. (2007), and Eames et al. (2011), to mention some. These approaches are based on the reference evapotranspiration ET_0 which is calibrated based on full-scale observations. In this research the 24-h FAO Penman-Monteith equation – as described in Ventura et al. (1999), was used. This approximation is given by Eq. (1) below.

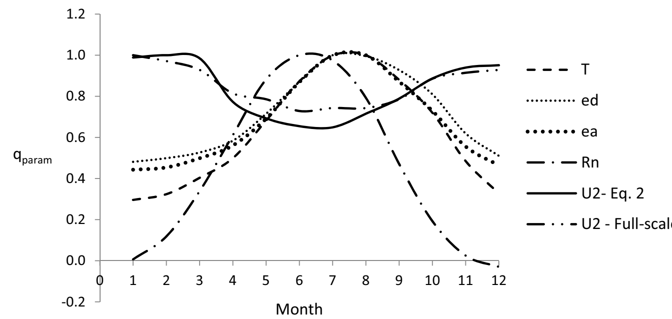

Fig. 1. Monthly average of environmental parameters related to *PET*.

$$PET = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273.16} U_2 (e_a - e_d)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

1 PET : grass reference evapotranspiration (mm day^{-1})
2 R_n : net radiation at crop surface (MJ m^{-2} day^{-1})
3 G : soil heat flux (MJ m^{-2} day^{-1}) – assumed to be zero as in Ekström et al. (2007)
4 T: mean temperature at 2 m height (°C)
5 U_2 : wind speed measured at 2 m height (m s^{-1})
6 (e_a-e_d) : vapour pressure deficit for measurement at 2 m height (kPa)
7 Δ : slope of the vapour pressure curve (kPa °C^{-1})
8 γ : psychrometric constant (kPa °C^{-1})
9 900 : coefficient for the reference crop (kJ^{-1} kg K day^{-1}) – see Allen et al. (1994)
10 0.34 : wind coefficient for the reference crop (s m^{-1})

Eq. (1) can be re-arranged as in Eq. (2a) in order to infer daily mean velocities of wind.

$$U_2 = \frac{PET(\Delta + \gamma) - X}{(YZ - 0.34\gamma PET)} \quad (2a)$$

where

$$X = 0.408\Delta(R_n - G); \quad Y = \gamma\frac{900}{T + 273.16}; \quad Z = e_a - e_d \quad (2b)$$

The equations to calculate all parameters for estimating U_2 in Eq. (2a) are given in Appendix B.

The data provided by the weather generator was passed through Eq. (2) and then averaged per month in order to establish a comparison with full-scale statistics issued by in Met Office (2013) —in terms of wind velocity. The results of the data processing for hundred scenarios of 30-years each are presented in normalised form in Fig. 1 whilst Table 1 provides the peak values of each environmental parameter. Note that full-scale measurements have been normalised by the peak simulated value in order to show the actual relationship between the two vectors.

In Fig. 1 is seen that the net radiation profile (R_n) is out of phase with respect to temperature (T) which might be due to the influenced of solar declination and relative distance with respect to the sun. Actual (e_d) and saturated (e_a) vapour pressure seem strongly correlated to T whilst the peak wind velocity occurs near the equinoxes, which is consistent with full-scale observations.