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# Modelling the effect of weather on moisture fluctuations in maize stalk residues, an important inoculum source for plant diseases

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ABSTRACT

Maize residues on the soil surface are a major inoculum source of several fungal pathogens of maize. Because the moisture content of crop residues can greatly affect fungal survival and inoculum production, we studied the effects of rainfall and relative humidity (RH) on the moisture content in maize stalk residues on bare soil and on soil under a wheat crop at the heading stage (i.e., when the canopy provides the maximum soil cover). The moisture content of residues that were initially saturated and that were then placed on soil outdoors declined to a minimum value after approximately 32 h. On each of the following days and in the absence of rain, the moisture content showed a diurnal pattern with decreasing values between 08.00 and 18.00 h and increasing values between 18.00 and 08.00 h. The pattern was the opposite for vapor pressure deficit. A simple model was developed to predict the wetting–drying dynamics of maize stalk residues based on environmental conditions. The model has three compartments: (i) wetting of maize stalk residues during rain; (ii) drying after rain; and (iii) diurnal fluctuations in the absence of rain. The model was calibrated and then validated against independent data collected in Italy and France. Comparison of observed vs. predicted data showed no systematic deviations of model predictions from real observations, with $R^2$ = 0.84 and standard error of estimates = 8.7%. The correlation concordance coefficient (=0.89) and model efficiency (=0.75) showed a satisfactory goodness-of-fit to the real data, with a slight overestimation (coefficient of residual mass = 0.11). The model should be a useful component of models for those plant pathogens, including *Aspergillus flavus*, *Fusarium verticillioides* and *Gibberella zeae*, that produce inoculum in maize residues.



## 1. Introduction

Crop residues are those parts of plants that remain in the field after the crops have been harvested (Kumar and Goh, 1999). They include plant parts not intended or unsuitable for harvest. The amount of crop residues often approaches or even exceeds that of the harvested crop (Takeuchi, 1987). For instance, for every 1 kg of dry corn grains produced, about 0.15 kg of cobs, 0.22 kg of leaves, and 0.50 kg of stalks are produced (USDA, 2011). The importance of proper disposal of residues has long been known, together with the usefulness of residues as organic materials, and their effects on soil cover, nutrient availability, soil structure, soil temperature, water evaporation, microbial activities, and insect populations (Unger, 1994 in Quemada, 2004; Stroo et al., 1989; Takeuchi, 1987).

Plant residues also play an important role as inoculum sources of many plant pathogens because they often include parts of diseased plants (Takeuchi, 1987). A portion of these residues is usually ploughed into the soil after crushing, and another part remains on the soil surface, but the increase in no-till or reduced tillage methods has increased the amount of crop residue left on the soil surface (Aziz et al., 2013; Kumar et al., 2012; Klein et al., 2001; Baird et al., 1997). The presence of a residue layer results in wetter and cooler conditions on the soil surface than on bare soil, and such residues and conditions favor the increase in pathogens (Cook and Haglund, 1991; in Kumar and Goh, 1999). Many pathogens overwinter in crop residues and use them as a substrate for inoculum production during the following growing season, suggesting that no-tillage systems can contribute to the survival and growth of plant pathogens (Sturz et al., 1997). On the other hand, plant disease-causing pathogens developing in both soil and crop residues may be controlled by natural enemies inhabiting the soil or litter (Whalen et al., 2007).

Maize residues have been considered a major inoculum source of fungi pathogenic to maize (Jaime-Garcia and Cotty, 2010; Palaversic et al., 1994), such as *Aspergillus flavus* (which is the causal agent of Aspergillus ear rot), *Bipolaris maydis* (Southern corn

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leaf blight), *Cercospora zeae-maydis* (gray leaf spot), *Colletotrichum graminicola* (anthracnose leaf blight and stalk rot), *Exserohilum turcicum* (Northern corn leaf blight), *Fusarium graminearum* and *Fusarium verticillioides* (Fusarium ear rot), *Kabatiella zeae* (eyespot), and *Stenocarpella macrospora* and *Stenocarpella maydis* (ear and stalk rot) (Reis et al., 2011; Cotten and Munkvold, 1998). These fungi can survive on maize debris as saprophytes for many months (up to 2 years for *F. graminearum* and *F. verticillioides*; Pereyra and Dill-Macky, 2008; Cotten and Munkvold, 1998; Khonga and Sutton, 1988) in the form of overwintering mycelium, conidia, or they survive through resting structures, such as chlamydospores or sclerotia.

The relevance of crop residues as an inoculum source depends on the amount of residue at harvest, residue decomposition rate between cropping seasons, saprophytic growth of the pathogen in the residues, and microbial activity in the residue, which may influence both residue degradation and pathogen growth (Bailey and Lazarovits, 2003; Kumar and Goh, 1999; Sturz et al., 1997). The above factors are all influenced by aeration, pH, available nutrients, lignin content, age and size of material, and especially by temperature and moisture in the residue layer (Stott et al., 1986; Parr and Papendick, 1978; Waksman and Gerretsen, 1931). Survival of fungal pathogens tends to be greater in residue that resist breakdown (as for *F. graminearum* in wheat, Sutton, 1982), in residues at the soil surface in some cases (as for *C. graminicola* in maize, Lipps, 1983; *C. graminicola* in sorghum, Casela and Frederiksen, 1993; *Fusarium* spp. in maize residues, Cotten and Munkvold, 1998), and in residues buried in the soil in other cases (as for *A. flavus*, Wicklow, 1987).

Crop residues are then a key element in the epidemiology of several pathogenic fungi. For these fungi, survival, inoculum production, and dispersal are greatly influenced by the environment, primarily temperature and moisture at the crop residue level. A clear example of this is Fusarium head blight (FHB), caused by a complex of *Fusarium* species of which *F. graminearum*, the anamorph of *Gibberella zeae*, is often predominant, which is one of the most widespread and dangerous diseases of wheat (McMullen et al., 2012). Ascospores are the prevalent form of FHB inoculum and are mainly produced in perithecia in the residues of the previous crops, including maize (Osborne and Stein, 2007). The main factors influencing production of perithecia and ascospores are light (Tschanz et al., 1976), temperature (Dufault et al., 2006), and moisture (Manstretta, 2015). Therefore, information on the moisture content of the crop residues is essential for assessing the dynamics of inoculum production, and thus, the risk of infection.

The moisture content of plant residues on the surface of bare or cropped soils changes over time and is driven by the physical principles governing the soil–water system and particularly by the water cycle in the field (Hillel, 2012). A number of detailed, mathematical models have been developed that describe the thermo-hydraulic properties of soil systems. One recent example is the HYDRUS model (Radcliffe and Simunek, 2010). However, such models are not appropriate for the practical purpose of predicting the moisture content of maize residues in a particular environment because the models use a large number of parameters, many of which are difficult to estimate (e.g., soil hydraulic properties comprising the water retention curve and the hydraulic conductivity function) (Simunek et al., 2012). Other models have been developed that consider the environmental conditions in the residue layer above the soil with the purpose of estimating the decomposition rate of residues and to predict nutrient recycling or the effect of residues on soil erosion (Scopel et al., 2004; Henriksen and Breland, 1999; Jans-Hammermeister and Mcgill, 1997). The model of Bristow et al. (1986), for example, describes the soil–residue–atmosphere interaction for heat and moisture and simulates various parameters in the residue layer, such as short and long wave transfer, changes in energy status, rainfall interception, infiltration, redistribution, evaporation, and drainage. This model requires many inputs, some of which are difficult to obtain or estimate.

To our knowledge, a simple model that describes the wetting–drying dynamics of maize stalk residues based on environmental conditions is unavailable in the literature. The aims of the present work were: (i) to study the fluctuations of moisture in maize stalk residues as affected by weather (i.e., rainfall, temperature, and relative humidity); (ii) to develop a mathematical model for predicting stalk moisture content in the field based on easy-to-collect data; and (iii) to validate the model by using independent data sets. In addition, the relationship between moisture content and water activity ($a_w$) of maize stalk residues was determined because this relationship is known for maize seed (Pixton and Warburton, 1971) but not for maize residues. Water activity is the partial vapor pressure of water in a substrate divided by the partial vapor pressure of pure water at the same temperature, and $a_w$ is widely used to predict the potential for microbial activity in a substrate (Marin et al., 1998a; Barbosa-Cánovas et al., 2007): higher $a_w$ substances tend to support more microbial growth.

## 2. Materials and methods

### 2.1. Collection of maize stalk residues

Because pathogenic fungi usually produce inoculum in residues that have overwintered and partially decomposed in the field, maize stalks were collected in the spring of 2011 and 2014 in commercial fields of the Po Valley (North Italy). Decomposition alters the density and water retention properties of the decaying tissue (Iqbal et al., 2013). The density of our maize stalk residues was $0.06 \pm 0.01$ g dry weight (DW)/m$^3$. Stalks were cut into 5-cm-long pieces (to have pieces uniform in size and similar to those resulting from residue crushing in field; Iqbal et al., 2013) and stored in a dry and cool environment until used to avoid microbial growth.

### 2.2. Determination of moisture content, $a_w$, and the relationship between moisture content and $a_w$

Stalk pieces were individually weighed (fresh weight, FW in g) at the beginning of each of the three experiments described below with a two-digit analytical balance (Sartorius BL500S, Sartorius Italy s.r.l., Monza Brianza, Italy). FWs were determined at different time intervals during the experiments (see below). At the end of each experiment, stalk pieces were dried in an oven at 120 °C for 48 h, and the DW was measured. Moisture content ($M$ in %) was finally calculated as: $M = [(FW - DW)/FW] \times 100$.

To determine the relationship between moisture content and water activity ($a_w$) of the stalk residue, five stalk pieces were placed in plastic boxes ($12 \times 9 \times 7$ cm) at 62.5, 75.5, 85.0, 92.5, and 100% RH. These RH levels were obtained with saturated aqueous solutions of $NH_4NO_3$, NaCl, KCl, $KNO_3$ (Dhingra and Sinclair, 1995), and water, respectively. The RH in the trays was confirmed with data loggers (Tinytag Plus 2 TGP -4500, Gemini Data Loggers, Chichester, UK). The boxes (two per RH level) were kept at 25 °C. After 3 weeks, the stalks were cut into 4 mm pieces, and the $a_w$ was measured using an AquaLab LITE water activity meter (version 1.3, Decagon Devices Inc., Pullman, WA). To determine the relationship between moisture content and $a_w$ in the residues, $a_w$ data were regressed against moisture data by using the Chen–Clayton equation (Chen and Clayton, 1971).

### 2.3. Experiments on the moisture content of maize residues

The maize stalk residues were used for three experiments concerned with: (i) water absorption in residues during rain (experiment 1); (ii) the drying of residues after the residues have absorbed