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APPLICATION OF A LAGRANGIAN MODEL FOR POLLEN DISPERSION

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1 INTRODUCTION

Adoption of genetically modified crops has led to increased interest in evaluating and controlling pollen dispersion. In an open-pollinated crop such as maize, where the possibilities of adventitious pollen contamination are high, current knowledge is insufficient to accurately predict the levels of outcross to be expected in a field. Open pollination conflicts with the need to limit genetic drift and control genetic purity of harvested seeds, and limits the success of seed producers striving to fulfill market demand for genetically pure products. Therefore, assessing the risk of out-crossing events is critical. Any such assessment must consider the complex interactions between the biology of flowering and pollination processes and the physical nature of pollen transport in the atmosphere.

Pollen dispersal from maize fields has been examined in a number of studies (Jones and Newell, 1946; Raynor et al., 1972; Paternaiani and Stort, 1974; Pleasants et al. 2001). Although previous studies have reported how far, and in what quantity, maize pollen can travel, these results cannot be used to predict the direction, distance or extent of pollen dispersal. Pollen transport in air was assessed after the fact by counting pollen grains on traps or by counting the percentage of out-crossed kernels. Various modeling approaches have been used to predict the movement of pollen grains in air (Di-Giovanni and Kevan, 1991; Di-Giovanni et al., 1995; Ashton et al. 2001; Aylor, D.E., 2002 personal communication). These models treat pollen grains as abiotic particles that move along simple diffusive-convective paths, either in normally-distributed Gaussian plumes or as independent particles following statistically random paths. Research on genetic purity has focused on only a few selected parameters that influence outcrosses. Efforts to date include estimates of pollen survival in the laboratory (Herrero and Johnson, 1980) and in the field (Raynor *et al*., 1972; Schoper *et al.* 1987a, b; Luna *et al.* 2001).

A realistic treatment of outcrossing must consider the interaction of multiple physical and biological processes. These include the nature of pollen production and shed, the impact of weather patterns on pollen dispersal and viability, and competition between locally-shed pollen and pollen delivered from elsewhere on the wind. To address this problem we are developing a coupled physical-biological model of outcrossing based on a Lagrangian model of pollen dispersion. The Lagrangian method is used for because of its generality and flexibility: first, the method readily accommodates flow fields of arbitrary complexity; second, each element of the material being transported can be identified by its source, time of release, or other properties of interest. The former allows us to better evaluate pollen dispersion in real-world flow conditions. The latter allows pollen viability to be estimated as a function of such factors as travel time, temperature, and relative humidity, so that the physical effects of airflow and turbulence on pollen dispersion can be considered together with the biological aspects of pollen release and viability.

In the following sections we give an overview of the pollen modeling framework. The coupled physical-biological model is not yet complete, but several of the components have been developed and are undergoing tests. Updated status and new results will be presented at the conference.

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2 THE COUPLED PHYSICAL-BIOLOGICAL MODEL

2.1 Overview

The model is a collection of sub-models that are being merged to produce a tightly coupled physical-biological framework that traces pollen from its production and shed, through its transport in the atmosphere, and finally to its viability at a receptor (here, another plant). A conceptual outline of the approach is given in Figure 1. In the following subsections we briefly describe the individual components of the coupled model.

2.2 Meteorological input data

The pollen model is designed to be flexible as to meteorological input data that are used. For agricultural applications, observed data often are limited to basic meteorological variables at a single point. In such instances we rely on similarity theory to extrapolate the meteorological data into three-dimensional space. Other applications may use results from atmospheric models or operational analyses.

2.3 Source submodel

Accurate calculations of pollen concentrations in the atmosphere and pollen deposited at a receptor depend critically on accurate estimation of the amount of pollen produced. Westgate et al. (2002) have taken advantage of the predictable nature of tassel development and the process of pollen shed from the staminate flowers to establish quantitative relationships between tassel development and pollen shed. Their techniques revealed that pollen shed on a field scale typically occurred over a period of 10 to 12 days and peaked 2 to 3

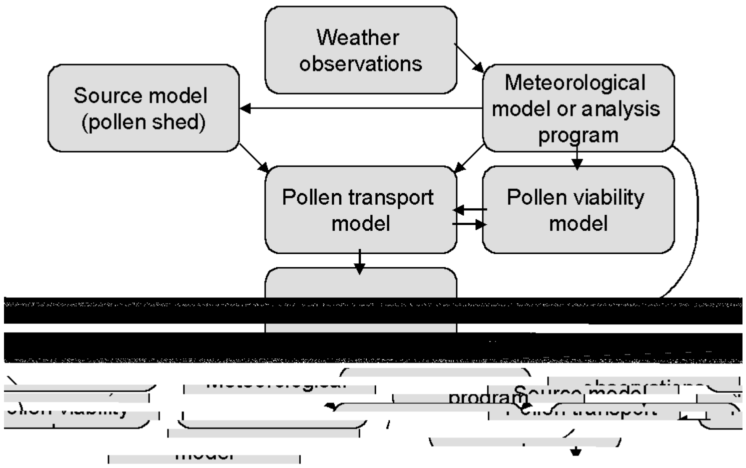

Figure 1: Conceptual diagram of the coupled physical-biological pollen model. Arrows indicate directions of the main information flows.

days after anthesis (Westgate et al. 2002). The amount of pollen produced for a typical modern hybrid was about 3×10^{11} pollen grains ha^{-1}, corresponding to about 4.4×10^{6} pollen grains per plant. Such measurements allow us to evaluate pollen production on a field scale and thereby define source activity.

2.4 Transport and diffusion submodel

We have tested EPA's Gaussian plume models for their capacity to quantify the transport of pollen away from maize fields (Ashton et al. 2001, Westgate et al. 2000). These models estimate both the quantity and direction of pollen movement fairly accurately, but are restricted to applications where the surrounding terrain is simple and the flow field is simple. Thus, their applicability for assessing pollen dispersal across the variety of surface and weather conditions encountered in maize production is limited. An alternate method to the Gaussian approach is based on Lagrangian stochastic techniques, in which the frame of reference is the material being dispersed and a stochastic (or random-walk) approach is used to account for the effects of turbulence on movement of the material. The Lagrangian-stochastic method represents the material being transported as a collection of discrete elements (often referred to as virtual "particles") rather than a continuous plume. Development of the transport and diffusion submodel follows basic criteria for validity of a Lagrangian stochastic model derived by Thomson (1987).

The Lagrangian approach has essentially no limitations with regard to the complexity of the flow in space or time. This allows us to evaluate pollen transport in highly non-uniform winds. For example, winds in the vicinity of a shelter belt could not be realistically included in a Gaussian model, but we have driven the transport and dispersion submodel using wind and turbulence fields from the shelter belt model formulated by Wang et al. (2001). An example of predicted pollen flow around a shelter belt is shown in Figure 2. The pollen transport submodel is being compared to field measurements gathered in a previous project and to results from a standard EPA dispersion model.

Maize pollen grains have a high settling velocity (of order 20 cm/s), which profoundly affects their dispersion. The simplest method for including the effects of settling in a Lagrangian model is to superimpose a terminal fall speed onto the vertical component of the particle's motion. Wilson (2000) finds this approach to be adequate in most circumstances compared with more complex inertia-particle approaches. He notes further that uncertainties in calculating particle deposition to a canopy are more important than the details of the Lagrangian transport method. At the present stage of development we have adopted the simple settling-velocity approach.

We are exploring a variety of methods for using predicted virtual-particle locations to estimate the surface pollen burden. The simplest approach is to count the number of virtual particles deposited in each unit area. The main disadvantage of this approach is that large numbers of particles are required in order to obtain reliable estimates of concentrations. Statistical approaches are being explored that have the potential to yield more robust concentration estimates for a given number of virtual particles (thus allowing fewer particles to be used). Both parametric methods and kernel density estimation techniques are being tested.

2.5 Pollen viability submodel

As discussed previously, the Lagrangian approach allows us to track individual elements of the pollen cloud. In particular we know the physical environment (temperature, humidity, etc.) at each point along the element's path, so that environmental effects on pollen viability can be incorporated into the model. Viability is reduced at high temperatures and low humidities (e.g., Herrero and Johnson, 1980; Luna et al., 2001). Thus, a portion of the pollen cloud that reaches a receptor via a trajectory where temperature is low and humidity is high would have greater viability than one that reaches the same receptor by traveling through hotter and drier air.

We will take advantage of the "tagging" capability of the Lagrangian method to quantify these effects of environmental conditions on pollen viability through implementation of a pollen viability submodel. The viability submodel will be based around a pollen aging

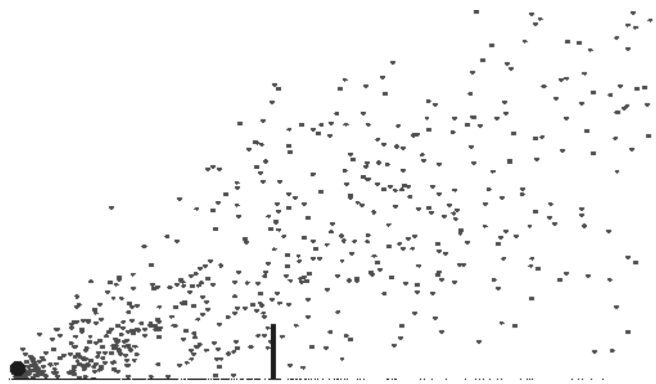

Figure 2: Prediction of pollen dispersion around a 10 m high agricultural shelter using the shelter belt model of Wang et al. (2001) to obtain wind and turbulence fields. The source location is given by the heavy dot and the shelter is indicated by the heavy vertical line.

function that expresses pollen viability in terms of time-integrated temperature and humidity along the pollen trajectory. We suspect that previously reported effects of relative humidity and temperature on pollen viability (e.g., Luna et al., 2001) in fact reflect an underlying relationship to atmospheric water demand as represented by vapor pressure deficit. Published data do not provide an adequate basis to accept or reject this hypothesis, so we will test the water-demand hypothesis using data collected in the field component of our study during the 2002 growing season.

2.6 Receptor submodel

When foreign pollen enters a field, it must outcompete local pollen to achieve an outcross. The outcome of this competition is affected by physical factors (e.g., local pollen density), genetic factors (e.g., pollen-silk compatibility and relative rates of pollen tube growth), and environmental factors (e.g., wind speed and direction, relative humidity, temperature). Luna (2001) reported that for hot, dry conditions no outcrosses occurred beyond 200 m from the pollen source. Receptor plants were not detasselled; thus, adventitious pollen had to compete with a heavy cloud of local pollen. In those experiments it was not possible to determine whether adventitious pollen amount, pollen viability, or failure to compete with locally-produced pollen ultimately controlled the observed level of out-crossing.

Results from our research on pollen shed indicate that a minimum density of pollen shed of about 3000 pollen grains per exposed silk is required to ensure maximum kernel set (Westgate et al., 2002). At lower levels of pollen shed, kernel set decreases dramatically, possibly leading to increased risk of out-crossing.

2.7 Risk assessment submodel

The ultimate product of the model will be a quantitative assessment of the likelihood and degree of outcrossing between adjacent fields. This information can then be used as a component of risk assessment, which must be considered in light of acceptable levels of contamination dictated either by regulatory standards or by market forces.

3 SUMMARY

We have described a modeling framework for coupling the physical mechanism of pollen transport and diffusion with the biological processes involved in pollen shed and viability. The model is designed to be flexible as to the input data that are used and general as to the variety of real-world conditions that can be treated.

The project also will provide the crucial element of field verification to assess the skill and limitations of the model, and the aspect of the model that are most in need of improvement. As noted by Emberlin et al. (1999) most prior studies of pollen dispersion have been performed for only a narrow range of weather conditions, so that it is essential to obtain measurements for verification when a model is applied in a particular environment. The model will be continuously evaluated with results from field studies in realistic applications.

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