2007

Numerical simulations of maize pollen dispersal

Craig Andrew Clark
Iowa State University

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Numerical simulations of maize pollen dispersal

by

Craig Andrew Clark

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Agricultural Meteorology

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2007

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ABSTRACT

The open pollination of maize raises the possibility of outcross of conventional and organic varieties with adventitious pollen from a genetically-modified source field. Analysis of potential outcross requires knowledge of atmospheric flow and subsequent pollen dispersal. The flow fields are often complex. When small maize plots are surrounded by a shorter crop such as soybean, the step function in surface characteristic substantially alters the flow within and near the maize field. Tall field-edge borders also affect the flow, with the potential of reducing pollen dispersal away from the source field. This three paper study explores the dispersal of pollen from maize fields, as well as the effect of a tall field-edge border on flow and dispersal.

For this purpose, a three dimensional Lagrangian particle dispersion (LPD) model has been adapted for maize pollen dispersal and validated with field studies from Iowa in August 2003 and 2005. Millions of particle trajectories were simulated following a random flight approach; each particle is tracked and the resulting pollen cloud is proportional to the ensemble of particles. The flow fields required to drive the LPD were provided by scaling laws valid within the atmospheric surface layer (paper one) or by three dimensional implementation of the Wang and Takle (WT) shelterbelt model (papers two and three). The shelterbelt model provides physically consistent flow fields and allows better analysis of the sensitivity of pollen dispersal to flow characteristics.

The dispersion model generates a realistic pollen deposition plume for the 2003 cases, similar in shape to the observations (paper one). Using flow fields from scaling relationships to drive the LPD, for the case of maize surrounded by soybean, the model explains most of the observed location to location pollen deposition variability. The model doesn’t produce
enough downwind deposition far from the field, due in part to the lack of realistic vertical velocity. Using WT flow fields and releasing much more pollen also produces realistic deposition patterns, but there is an over-prediction of pollen far from the field (paper two). Since the model produces realistic deposition patterns, it is a useful assessment tool to explore the sensitivity of dispersal to flow properties. Sensitivity tests revealed that the maize field reduces pollen transport downwind of the field due to a reduction in wind speed, while the altered turbulence and vertical velocity tend to slightly increase dispersal away from the field.

The observed effect of a field-edge border was explored in paper three. With the addition of a sorghum border at field edge, there is modestly less observed long-range deposition. The simulations produced realistic spatial patterns of particle deposition that included the sharp near-source deposition gradient and longer-range dispersive tail. However, the model produced too little pollen at mid distances from the field (~30 to 50 m) and over-predicted pollen at larger distances (> 50 m), with a dispersive plume that appears too wide. Some of this far-field error may be due to differences in sampling, since the model employs a larger count region than the pollen traps. Comparing the simulated border and control deposition, the chief differences are a modest increase in within-field deposition and a slightly faster downwind decrease in deposition with distance for the border field. This results in increased downwind pollen deposition for the control field. The simulated effect of the border on long-range dispersal is small in absolute terms, but large in relative terms (with up to a 50% reduction at some downwind locations). This suggests that field-edge borders may reduce pollen dispersal enough to reduce the likelihood of outcross with neighboring fields. The model sensitivity to border characteristics is modest, even when the border height
is increased by 1 m. On the other hand, a simulation with upwind flow imposed over the domain results in decreased within-field deposition and substantially increased pollen within ~150 m of the field. This indicates that the maize field itself has a substantial sheltering impact.
CHAPTER I. GENERAL INTRODUCTION

1.1 Problem statement

The open pollination of maize, in which pollen is dispersed by the wind, and development of genetically modified (GM) germplasm have led to increasing interest in the analysis and prediction of pollen dispersion and potential outcross. Outcross between GM maize with organic or conventional varieties may have trade or legal consequences (as noted by Aylor et al. 2003; Jemison et al. 2001, etc.). There is also concern that GM maize will outcross with ancestors of maize (as addressed in Garcia et al. 1998). Growers in the U.S. follow standards set by state seed agencies and federal guidelines, with minimum distance between fields determined in part by border rows, size, barriers, and flowering dates (Baltazar and Schoper 2002; Ireland et al. 2006). Current isolation guidelines may not be meeting the demands of international trade partners, particularly the European Community (Rogers and Parkes 1995). Unfortunately, current knowledge is insufficient to accurately predict the level of outcross. Quantitative assessment is required and must consider both crop biological processes and pollen transport in the atmosphere (Aylor et al. 2003).

Observations of pollen deposition indicate how far pollen traveled in specific cases, but cannot be generalized to other field and atmospheric conditions. Numerical simulations may be useful for predicting pollen flow. Model sensitivity tests can assess the importance of flow characteristics and reveal the extent to which simulated results may be generalized to different environmental conditions. In order to realistically predict pollen transport, three dimensional flow fields must be estimated from scaling relationships or simulated using dynamical models. In an idealized setting of a large homogeneous maize field, the flow
characteristics may be accurately estimated from single point measurements. Flow estimation is more difficult in many natural settings and field experiments, in which non-homogenous surface characteristics produce complex flow fields. Roughness changes alter the horizontal and vertical mean wind, as well as turbulence. This has the potential for significant impacts on maize pollen dispersal, with implications for the generalization of experiment results to other field configurations. The impact of shelter on atmospheric flow further raises the possibility that pollen dispersal away from the field and subsequent outcross may be reduced by the addition of a taller vegetative border around the maize field.

This dissertation tests the hypothesis that flow properties near maize fields determine the dispersal of maize pollen, as well as the ability of Lagrangian particle simulations to predict the dispersal. This study further tests the hypothesis that field edge borders reduce the wind speed over the source field and subsequently reduce dispersal of pollen away from the field. The three papers explore the following issues.

1. The extent to which three dimensional Lagrangian particle simulations accurately predicts pollen deposition is explored using an upwind weather observation and scaling laws to estimate the flow fields.

2. The Wang and Takle (1995a) shelterbelt model is adapted to three dimensions and used to initialize Lagrangian particle simulations. The results are tested against observed pollen dispersal.

3. The effectiveness of a tall field-edge border at reducing pollen dispersal away from the field is examined using the Wang and Takle shelterbelt model to provide flow fields for the Lagrangian particle simulations. The model results are compared with field observations from 2005. The model sensitivity to border characteristics is also explored.
1.2 Dissertation organization

This dissertation consists of three papers designed as journal articles, with a general introduction and conclusion placing the papers in a larger context. Each paper will explore aspects of the work including numerical modeling, analysis of observations, and numerical sensitivity tests. The three papers are as follows:

Paper 1: “Lagrangian Numerical Simulations of Canopy Air Flow Effects on Maize Pollen Dispersal” by Raymond W. Arritt, Craig A. Clark, A. Susana Goggi, Higinio Lopez Sanchez, Mark E. Westgate, and Jenny M. Riese

The principal authors of this paper were Craig Clark and Ray Arritt; Ray Arritt developed the Lagrangian particle model, while Craig Clark made model adaptations and performed the model simulations and both authors performed analysis. Jenny Riese aided in earlier model validation, while Mark Westgate, Susana Goggi, and Higinio Lopez Sanchez were instrumental in collecting the field data and placing the results in a larger context.

Paper 2: “Application of a Shelterbelt Model for Lagrangian Simulations of Maize Pollen Dispersal” by Craig A. Clark, Raymond W. Arritt, A. Susana Goggi, Higinio Lopez Sanchez, Gene S. Takle, and Mark E. Westgate

The principal author of this paper was Craig Clark. Ray Arritt helped with model development and analysis of the results. Gene Takle aided model development, while Mark
Westgate, Susana Goggi, and Higinio Lopez Sanchez collected the field data and placed the results in a larger context.

Paper 3: “The Observed and Simulated Effect of a Field-Edge Border on Maize Pollen Dispersal” by Craig A. Clark, Raymond W. Arritt, Gene S. Takle, Mark E. Westgate, Juan Astini, and Susana Goggi

The principal author was Craig Clark. Ray Arritt helped with model development and analysis of the results, as well as the collection of field data. Gene Takle aided model development and analysis, while Mark Westgate, Juan Astini, and Susana Goggi collected the field data and placed the results in a larger context.

1.3 Literature review

1.3.1 Maize pollen dispersal

Maize pollen is released from an opening at the anther tip. Earlier estimates of pollen shed were 25 million pollen grains per tassel (Kiesselbach 1949). Due to modern planting practices, typical hybrid tassels produce 3 to 4 million pollen grains (Halsey et al. 2005; Westgate et al. 2003). Pollen shed typically occurs from early morning through mid afternoon (Ogden 1969), with timing correlated with canopy wetness and vapor pressure deficit. Drier atmospheric conditions promote pollen release (Loubet at al. 2002), while strong winds promote earlier shed (Raynor et al. 1972). The timing of shed affects the dispersal of pollen, since the wind characteristics vary. The timing also affects the nick, or temporal alignment of pollen shed and silk emergence (Aylor et al. 2003).
The diameter of maize pollen significantly affects its dispersal. Maize pollen has a large diameter (~75 to 100 µm) and thus a large settling velocity (20 to 30 cm s\(^{-1}\)). Measurements (Aylor 2002) indicate that loss of water content over time reduces the size of pollen grains, while the density of the pollen grains increases. The subsequent settling velocity is reduced from 31 cm s\(^{-1}\) at full hydration to 17 cm s\(^{-1}\) for dry pollen.

Given the relatively large settling velocity values, it is not surprising that most pollen is deposited inside the source field, with deposition decreasing rapidly with distance from the source field. Raynor et al. (1972) found that roughly twice as much pollen fell inside the source field as outside it, while Loubet et al. (2002) found that maximum deposition occurred within 1 to 3 m of the source field. Looking at maize pollen deposition on milkweeds, Pleasants et al. (2001) found average values of ~170 grains cm\(^{-2}\) inside the field and 14 grains cm\(^{-2}\) outside the field. Jarosz et al. (2003) found deposition rates at 32 m from the source field less than 10% of those at 1 m, with 99% of emitted pollen deposited within 30 meters of the source field. The same study reports airborne concentrations reduced by a factor of 3 between 3 and 10 m downwind of the field. These observed deposition patterns imply that pollination is most typically from a nearby source; Emberlin et al. (1999) found that 50% of the kernels of an individual plant result from pollen released within a 12 m radius.

This does not indicate, however, that no outcross will occur at large distances from the source field. A small fraction of pollen will be lifted by large upward turbulent velocities and carried greater distances from the field (similar to the seed transport process discussed in Nathan et al. 2002a). As explored by Aylor et al. (2003), the pattern of dispersion away from the source resembles a tail, with low amounts of pollen traveling large distances from the
source. They also argue that the common exponential decay fit to outcross data is not adequate and predicts too little pollen far from the source. Brunet et al. (2003) found that pollen concentrations decrease with height near the ground, but are nearly constant through much of the mixed layer. This implies that large turbulent eddies (~1-2 km) in the boundary layer contain updrafts which overcome the terminal fall velocity and mix pollen throughout the layer. Since the wind speed increases with height near the ground, pollen which is lifted has the potential to travel much larger distances.

The importance of turbulence in the dispersal of pollen naturally raises questions regarding atmospheric stability. The results in paper 1 suggest that stability is a secondary factor, with higher wind speeds being responsible for long-range pollen transport. However, these results may not adequately reflect the role of stability in conditions approaching free convection (i.e. very light winds and large instability). Tackenberg et al. (2003), using a trajectory model, conclude that unstable conditions with light winds promote greater dispersal than higher wind speeds. Soons et al. (2004) argue persuasively that the Tackenberg et al. conclusion is incorrect, due to the use of a single point vertical velocity observation with generally positive vertical velocities (which would be location specific). They further point out that strong turbulence associated with greater wind speeds will produce greater dispersal distances when modeled with realistic turbulent vertical velocity autocorrelation. While the free-convective case needs further study, it is likely that greater dispersal is generally associated with higher wind speeds.

Jarosz et al. (2003) provide an analysis of the vertical pollen flux downwind of the field at a height of 3 m, indicating convective, diffusive, gravitational settling, and turbophoretic components of the flux. The (locally) downward convective flux is associated
with the downward mean vertical velocity caused by the roughness change. Roughness changes induce vertical velocities, with upward motion at the leading edge of smooth to rough transitions and subsidence at the leading edge of rough to smooth transitions. The diffusive flux is positive, since the height of analysis is above the canopy. The small counter-gradient turbophoretic results from the gradient of turbulent kinetic energy near the surface, but is difficult in practice to assess (as discussed by Wilson 2000).

The amount of locally produced pollen is also important to any assessment of outcross risk. Westgate et al. (2003) found field-scale pollen shed occurred over a 10 to 12 day period and peaked 2 to 3 days after anthesis. Typical plants produced $\approx 4.4 \times 10^6$ pollen grains and maximum kernel set required pollen shed of $\approx 3000$ pollen grains per exposed silk. Kernel set decreases significantly with reduced pollen shed, which may increase the risk of outcross. Outcross requires that adventitious pollen out-compete local pollen; local pollen density, genetic factors, and environmental factors influence the outcome of this competition.

Pollen viability also influences potential for outcross. The rate of viability loss is largely determined by environmental vapor pressure deficit, while being insensitive to the direct effect of solar radiation (Aylor, 2004). Fonseca and Westgate (2005) discussed the reduction in pollen viability as exposure to the air reduces the water content. Viability was $\approx 79\%$ initially for a moisture content of $\approx 60\%$, but decreases to virtually no viability at $30\%$ moisture content. Aylor (2004) found that germination is reduced by $50\%$ within 60 to 240 min of exposure, while the Fonseca and Westgate (2005) results indicate a $50\%$ viability reduction within 11 to 25 min given typical summertime temperature and relative humidity. In the turbulent boundary layer, the reduction of viability during flight is a function of the particle trajectory and the vertical profiles of temperature and relative humidity. For warm
and dry conditions, Luna et al. (2001) found that outcross was eliminated beyond 200 m. Based on Fonseca and Westgate (2005), viability can be estimated along the path of each simulated particle. For the field conditions simulated in this thesis, pollen grains remained viable inside the model domain. This is not the case for pollen that travels far outside the model domain, or in cases of free convection.

Observations of pollen dispersal indicate how far pollen travels in specific circumstances, but cannot be generalized to other crop and atmospheric conditions. Numerous mechanistic approaches to the problem of seed and pollen dispersal have been used, with various levels of complexity. Several models predict straight-line trajectories using a single wind speed during the trajectory (e.g. Anderson 1991; Greene and Johnson 1996; Nathan et al. 2001, 2002b). The advantage of this approach is relative simplicity, but accuracy is reduced far from the field (as noted by Nathan et al. 2001, 2002b). Bullock and Clarke (2000) compare seed data with the Greene and Johnson model and exponential and power law empirical models, concluding that the dispersive tail is underestimated in each case. Klein et al. (2003) used a quasi-mechanistic approach, in which physical considerations (including Brownian motion) were used to develop a model subsequently fit to observed data.

Several studies of pollen and seed dispersal have used Lagrangian random flight simulations (Jarosz et al. 2004; Aylor et al. 2006, Aylor et al. 1006; Di-Giovanni et al. 1995). This approach has also been used in related dispersion applications, such as the dispersal of glass beads (Wilson 2000) and spores (Aylor and Flesch 2001). With the Lagrangian particle dispersion (LPD) technique, the frame of reference is a virtual pollen grain and a random-walk approach is used to account for the effect of turbulence on dispersion. Jarosz et al.
(2004), using a two dimensional approach (one horizontal coordinate aligned with the wind and a vertical coordinate) similar to Aylor and Flesch (2001), found that the model correctly simulated maize pollen concentration levels in the boundary layer, but under-predicted pollen deposition near the field. They suggested that model error was likely the result of not fully representing the turbulent flow regime at the roughness transition at the edge of the field.

1.3.2 Properties of boundary layer and canopy flow

Pollen movement in the atmosphere is largely determined by the mean and turbulent flow fields. Pollen dispersal takes place within the planetary boundary layer, which may be broadly defined as the region which responds to surface forcing within an hour or less (Stull 1988 provides an excellent qualitative and quantitative boundary layer description). This surface/atmospheric interaction within the boundary layer is manifested as turbulent fluxes of heat, moisture, and momentum. The largest turbulent eddies span the depth of the boundary layer (~1 to 2 km during the daytime). Large eddies are generated by both the mechanical forcing of wind shear and daytime instability near the surface. The turbulent energy cascades to smaller scales (i.e. smaller eddies), with dissipation at the molecular scale. Turbulent fluxes result as eddies transport air parcels through gradients of heat, moisture, momentum, and other tracers. While horizontal advection by the mean wind dominates in the horizontal direction, turbulent transfer is dominant in the vertical direction within the boundary layer.

The surface layer is the subset of the boundary layer near the ground, in which the turbulent fluxes are roughly constant with height (or vary less than 10%). Within this surface layer, which typically constitutes the lowest ~10% of the boundary layer, the mean wind
speed follows the logarithmic wind profile during near-neutral conditions (Stull 1988; Garrett 1992):

\[ u(z) = \frac{\phi_m u_*}{k} \ln\left(\frac{z}{z_0}\right) \]  

(1)

Here \( z_0 \) is the roughness length (or parameter), which represents the height of the zero mean wind speed of the log wind profile; it varies with surface characteristic, but may be estimated as ~1/10 of the canopy height (Hurtalova et al 2002). For tall canopies, the log profile is adjusted using a displacement length, which may also be estimated as ~2/3 of the canopy height (Hurtalova et al 2002). Although the average turbulent velocity is zero, friction velocity (\( u_* \)) represents a characteristic wind speed of the turbulent eddies. The non-dimensional wind profile (\( \phi_m \)) adjusts for the case of non-neutral stability, in which vertical momentum transfer is enhanced. As summarized by Garratt (1992), this empirical parameter may be determined using the Monin-Obukhov length or bulk Richardson number. The chief relevance of the log profile for pollen dispersal is that the wind speed increases rapidly with height near the ground; as a result, pollen which is lifted has the potential to travel a much greater distance. In cases of extreme instability or stability, generally occurring with very light winds, the log profile is invalid.

The turbulent component of the flow also affects pollen dispersal and is particularly important in the vertical. Turbulent kinetic energy (TKE) is a useful characterization of the turbulent flow, since the variances of the three wind components contribute to the total TKE. For the simplified case with 2D flow, horizontal homogeneity, and a mean vertical wind speed of zero, the prognostic TKE equation (Stull 1988) is:
\[
\frac{\partial \tilde{E}}{\partial t} = \frac{g}{\theta_v} \left( w' \theta'_v \right) - u' w' \frac{\partial u'}{\partial z} - \frac{\partial}{\partial z} \left( w' \theta' \right) - \frac{1}{\rho} \frac{\partial w' \rho'}{\partial z} - D 
\] 

(2)

Here \( E \) is turbulent kinetic energy per unit mass, \( u \) is west to east wind component, \( w \) is vertical velocity, \( p \) is atmospheric pressure, and \( D \) represents viscous dissipation. The first term on the right hand side represents buoyant production or consumption of TKE, followed by terms for shear production, turbulent transport, pressure transport, and dissipation. In the typical daytime boundary layer, TKE is generated through mechanical and thermal production; turbulent and pressure transport terms subsequently transfer the TKE throughout the boundary layer (in other words, locations within the daytime mixed layer may have large amounts of TKE without any local generation).

The surface layer logarithmic wind profile and associated surface layer similarity relationships are invalid within and just above a plant canopy (up to \( \sim 4/3 \) the canopy height). Physical characteristics of the canopy significantly alter the flow within the canopy, with density, height, and flexibility all influencing the wind field (Ciono 1972). As noted by Wilson and Shaw (1977), vegetation extracts momentum from the flow, converts kinetic energy into wake-scale turbulence, and breaks up larger eddies into smaller ones. The wind speed is reduced in the canopy, with an inflection point (or “bulge”) in the velocity profile near the canopy top (Finnigan 2000; Raupach and Thom 1981). Despite the complexities of canopy flow, several approaches (e.g. Cionco 1972) generate a reasonable mean canopy wind profile that describes the mean wind reduction through the canopy (Raupach and Thom 1981). With crops such as maize, physical characteristics such as roughness length and displacement height change throughout the growing season (Hurtalova et al 2002).
Observations suggest that coherent turbulent structures are important within the canopy, with ejection-sweep cycles (Finnigan 2000). Raupach et al. (1996) explored these structures, which are generated by instabilities associated with the velocity inflection point and can generate locally counter-gradient fluxes. Their analysis of the turbulent kinetic energy budget reveals that diffusion transports turbulence deeper into the canopy, while wake production generates fine scale turbulence that is quickly dissipated. As a result of these processes, the turbulent intensity ($\sigma_u/u$, where $\sigma$ is the standard deviation of the wind component $u$) increases inside the canopy (Shaw et al. 1974). Wind gusts with 3 times the mean wind speed are more likely near the middle of the canopy than near the top (Shaw et al. 1979) and spectral analysis reveals that turbulence is anisotropic within the canopy, with a spectral roll-off of the along-flow horizontal component that is faster than expected in the inertial subrange (Shaw et al. 1974; Finnigan 2000). Turbulent eddies on scales larger than canopy are losing kinetic energy to heat and wake-scale turbulent energy, violating Kolmogorov assumptions in the inertial subrange (Finnigan 2000).

The effect of the canopy extends above its height. The roughness sublayer, extending up to roughly twice the canopy height, has larger eddy diffusivity and smaller gradients than the inertial sublayer above (Molder et al., 1999; Mahrt 2000; Cellier and Brunet 1992). Standard deviations of the wind components decrease in this layer, with a ~15% reduction from the surface layer value at the canopy top (Aylor and Flesch 2001). Calculation of fluxes within and above the canopy should not use a simple flux gradient relationship, since the length scale of the turbulence is larger than the scale over which significant vertical changes in the gradient occur (Wilson et al. 1982).
Internal boundary layers form as flow in equilibrium with one surface type passes over a surface with different characteristics, frequently with a sudden step change (Rao et al., 1974; Klipp and Mahrt 2003; Savelyev and Taylor 2001). As air passes over the new surface, the internal boundary layer (IBL) grows deeper until the surface layer flow is in balance with the new surface properties. Within the IBL, there is a fully adjusted layer extended from the ground and a layer above in which blending of the layers occurs (Garratt 1990). The IBL growth with distance approximately follows a 4/5 power law, whether defined by velocity or Reynolds stress (Shir 1972). The IBL is largely governed by the larger roughness length scale (Wood 1982), with a long fetch required for full equilibrium with the new surface (Taylor 1969). Based on field measurements (e.g. Bradley 1968; Munro and Oke 1975; Jegede and Foken 1999), empirical approaches in 2D have been used successfully to estimate the height of the IBL with distance from the step change (e.g. Savelyev and Taylor 2001, Panofsky and Dutton 1984, Wood 1982). These approaches don’t capture the full complexity of the flow near the step change; non-stationarity occurs near the layer of undulation, as the height of the transition zone shifts with time (Klipp and Mahrt 2003). Several 2D numerical models based on mixing length or turbulence closure have been developed to simulate IBL development (e.g. Shir 1972; Rao et al. 1974; Taylor 1969).

1.3.3 Shelterbelt flows

The sensitivity of pollen dispersal to flow properties raises the possibility that a windbreak may reduce pollen dispersal downwind of a source field. Windbreaks, which are simply structures that reduce wind speed, have likely been used since the dawn of agriculture to protect crops from excessively strong winds (Rosenberg et al., 1983; Wang et al., 2001).
Windbreaks may be natural, such as rows of trees (shelterbelts), or artificial, such as fences. Numerous studies report observations of flow near windbreaks (e.g. Wilson, 2004a,b), as well as wind tunnel data (e.g. Argent, 1992; Guan et al., 2003). Analytic solutions are problematic due to the complexity of the flow near windbreaks (Wang et al., 2001), but Reynolds-Averaged Navier Stokes (RANS) simulations (e.g. Wang and Takle, 1995a; Wilson, 1985) and large eddy simulation (Patton et al., 1998) have been successfully used to simulate the shelter effect.

The primary characteristics of a windbreak are its height (H) and porosity, with the most extensive wind speed reduction for windbreaks with roughly 40% porosity (von Eimern, 1964; Hagen and Skidmore, 1971; Wang et al., 2001). Windbreaks with reduces porosity generate less wind protection behind the shelter, while very dense shelters result in greater recovery further downwind. The wind minimum in the lee of a windbreak is roughly 5H or less behind the barrier, with a magnitude generally less than 40% of the upstream wind speed (e.g. Nord 1991; Bradley and Mulhearn, 1983). For a typical windbreak, the wind speed slowly recovers downwind of the minimum, with 80% of the upstream value at 20H (Raine and Stevenson, 1977). Some small effect on wind speed may still be felt at 30H or beyond (Jacobs, 1984; Bradley and Mulhearn, 1983).

For a given shelterbelt density, the shelter effect is largely insensitive to the width of the shelterbelt despite changes in the pressure field (Wang and Takle, 1996b). For porous windbreaks, the position of minimum wind speed shifts downstream, while higher density windbreaks have greater protection near the shelter and faster recovery (Hagen and Skidmore, 1971). The importance of vertical porosity distribution has been long debated (Heisler and Dewalle, 1988). Numerical simulations by Wilson (1987) suggest limited
sensitivity, although greater density at lower heights reduced mean wind speed close to the barrier.

Wang and Takle (1997b) discuss the importance of pressure perturbations, which are positive immediately upstream of shelter and negative in the lee, followed by a downstream plateau (see Figure 1.1 for an example of pressure perturbations and corresponding flow). The resulting pressure gradient in the lee opposes the flow and enhances the direct shelter effect of the drag force. Their analysis of the momentum budget reveals the importance of horizontal and vertical advection terms. The horizontal advection of the wind component perpendicular to the shelter is positive from the shelter to 5H downwind, with negative values near 10H (where the velocity gradient has reversed sign). Vertical advection nearly compensates the horizontal advection, with negative values to 7H and positive values near 11H. The vertical turbulent transfer is important (though not dominant), particularly near the top of the shelter where turbulent generation is greatest. The horizontal turbulent transfer is very small. Patton et al. (1998) present similar analysis, with vertical turbulent transport balancing horizontal advection.

With oblique flow, in which the wind direction is not perpendicular to the shelter, the reduction in wind is weaker and closer to the shelter (Seginer, 1975; Wang and Takle, 1996a; Wilson and Flesch, 2003). The reduction of shelter effect is greatest for angles exceeding 30° and may be the result of a change in shelter density, altered shelter efficiencies at different wind directions, and the shift in direction as the flow recovers downwind (Wang and Takle, 1996a). With a higher incidence angle, the increased drag force enhances wind speed reduction, while the increased parallel component reduces the shelter effect. As discussed in Wang and Takle (1996a), the enhanced drag effect is more important for low-density
shelters, while the latter effect is more important for dense shelters. The reduction is particularly acute for corners of rectangular plots, with little protection downwind of corners due to enhanced downward momentum transfer in the lee (Richards, 1984).

The shelter also influences the approach flow wind direction, first becoming more parallel and then shifting to more perpendicular as it moves through the barrier (Wang and Takle, 1995b; Mulhearn and Bradley, 1977). Pressure perturbations generate the shifts in wind direction: the positive perturbation ahead of the barrier opposes perpendicular flow, while the negative pressure perturbation in the near lee opposes perpendicular flow downwind of the pressure minimum. Across the barrier, the two perturbations act to support perpendicular flow (Wang and Takle, 1995b).

Interestingly, the effect of shelterbelts on mean and turbulent flow is largely insensitive to the shape of the barrier, despite changes in drag force and pressure (Wang and Takle, 1997a). The pressure loss coefficient is greater with less smooth shelterbelts. This results in greater flow deceleration close to the barrier, but greater acceleration in the near lee. Wang and Takle (1997a) conclude that the presence of both positive and negative pressure gradients in the lee of the shelter reduces the shape sensitivity. This further suggests the limitations of the pressure loss coefficient as an indication of shelter efficiency.

With an array of fences, the flow is more complex and difficult to adequately simulate (Wilson and Yee, 2000). Data from an ensemble of windbreaks (McAney and Judd, 1991; Judd et al., 1996) indicates that turbulent kinetic energy increases downstream of multiple barriers, ultimately reducing the shelter effect of subsequent barriers. The process is similar to internal boundary layer development, with the upwind breaks increasing larger-scale roughness (Judd et al., 1996) Furthermore, the strongest wind shear beyond the first
few breaks is located near the fence height, similar to profiles of a plant canopy (McAney and Judd, 1991).

Non-neutral atmospheric stability reduces shelter effect, although the influence disappears for oblique flow with greater than 30° (Wilson, 2004a). Jacobs (1984) found that unstable conditions promote increased turbulence and lead to faster recovery, while stable conditions the speed deficit right behind the barrier was reduced. This is supported by Nord et al. (1991), whom noted reduced sensitivity to the approach wind speed during unstable conditions. Despite the sensitivity to stability, the success of numerical simulations assuming neutral stability (e.g. Wang and Takle, 1995a) suggests that atmospheric stability effect is not a dominant factor in most cases.

1.3.4 Wang and Takle shelterbelt model

The flow fields used to drive the LPD in papers two and three were provided by the Wang and Takle (WT) shelterbelt model, which has been extended WT to 3D; to our knowledge, this is the first full 3D implementation of a shelterbelt model. Previous studies with WT model have simulated oblique flow, in which 3D wind components are simulated in 2D space. The WT model is non-hydrostatic and incompressible, and also assumes neutral stability. The model was developed using phase averaging followed by Reynolds averaging (Wang and Takle, 1995a,b, 1996, 1997a,b). Phase averaging was applied to the equations of motion and continuity equation over a scale smaller than scale of mean variation, yet larger than the individual shelter elements. This results in additional terms in the momentum and turbulent kinetic energy equation. The 3D equations for the horizontal (u,v) and vertical (w) motion and continuity relation are:
\[
\begin{align*}
\frac{\partial u}{\partial t} &= -\frac{1}{\rho_0} \frac{\partial p}{\partial x} - u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} - w \frac{\partial u}{\partial z} = \frac{\partial \overline{u}^2}{\partial x} - \frac{\partial \overline{u'v'}}{\partial y} - \frac{\partial \overline{u'w'}}{\partial z} - C_D \overline{A} \overline{u} u
\end{align*}
\]
(3)

\[
\begin{align*}
\frac{\partial v}{\partial t} &= -\frac{1}{\rho_0} \frac{\partial p}{\partial y} - u \frac{\partial v}{\partial x} - v \frac{\partial v}{\partial y} - w \frac{\partial v}{\partial z} = \frac{\partial \overline{v}^2}{\partial y} - \frac{\partial \overline{v'w'}}{\partial z} - C_D \overline{A} \overline{v} v
\end{align*}
\]
(4)

\[
\begin{align*}
\frac{\partial w}{\partial t} &= -\frac{1}{\rho_0} \frac{\partial p}{\partial z} - u \frac{\partial w}{\partial x} - v \frac{\partial w}{\partial y} - w \frac{\partial w}{\partial z} = \frac{\partial \overline{w}^2}{\partial z} - \frac{\partial \overline{w'w'}}{\partial z} - C_D \overline{A} \overline{w} w
\end{align*}
\]
(5)

\[
\left(\frac{\partial \overline{u}}{\partial x} + \frac{\partial \overline{v}}{\partial y} + \frac{\partial \overline{w}}{\partial z}\right) = 0
\]
(6)

The variables without primes are resolved grid-scale variables, while primes indicate parameterized turbulent components; \(u', v'\) and \(w'\) are horizontal and vertical turbulent components of the wind, \(U\) is the total wind speed, \(C_D\) is the leaf drag coefficient, \(A\) is the leaf area density (\(m^2\cdot m^{-3}\)), \(p\) is the pressure perturbation, and \(\rho\) is air density. Due to the small scale of shelterbelts, the Coriolis deflection is neglected. The terms on the right hand side represent pressure gradient force, horizontal and vertical advection (3 terms), turbulent diffusion (3 terms), and drag force per unit volume. The turbulent diffusion terms are parameterized following Mellor and Yamada (1982).

The turbulent kinetic energy (TKE) is determined from the following prognostic equation, in which \(\Lambda\) is a length scale multiplied by 16.6:

\[
\frac{\partial E}{\partial t} = -u_i \frac{\partial E}{\partial x_i} - u_i u_j \frac{\partial u_i}{\partial x_j} + \frac{\partial}{\partial x_i} \left( K_{ij} \frac{\partial E}{\partial x_i} \right) + C_D \overline{A} U^3 - \frac{(2E)^{2/3}}{\Lambda}; \quad i,j = 1,2,3
\]
(7)

The first term on the right hand side represents advection of TKE by the mean wind, followed by the shear production, turbulent transport, shelter-induced mechanical production, and dissipation. In the present study, horizontal and vertical advection terms are important
due to the sharp gradient of TKE near the shelter. The shear production term reflects the mechanical generation of TKE in high-shear regions. The turbulent transport terms diffuse TKE away from regions of maximum production, spreading out the zone of elevated TKE; although horizontal diffusion terms are included, the vertical diffusion term is more important. The shelter-induced mechanical term produces TKE as the drag force reduces the mean wind speed and converts mean kinetic energy to TKE. Since the shelterbelt model assumes neutral stability, the stability-dependent thermal production term in equation 2 is omitted here.

The turbulent fluxes required for the prognostic momentum and TKE equations are parameterized using turbulent transfer coefficients (K); for example, the kinematic turbulent vertical flux of the horizontal u component becomes:

\[-u'w' = K_m \left( \frac{\partial u}{\partial z} \right) \tag{8}\]

The turbulent transfer coefficients for momentum (K_m) and TKE (K_E) required for the turbulence closure are determined from turbulent kinetic energy, E, the empirical constant c (=0.74), and length scale l (determined from surface layer scaling).

\[K_m = K_E = cl\sqrt{E} \tag{9}\]

The model is initialized with the logarithmic surface layer wind profile, generated from single point wind data. The shelter configuration is provided via the leaf area density (A), which relates to the pressure loss coefficient (k_r) through the following relation (Wang and Takle, 1995b; Wilson, 1985):

\[k_r = \int_{-\infty}^{\infty} C_D A dx \tag{10}\]
The prognostic equations of motion and TKE equation are discretized on a finite difference grid. A modified Crank-Nicholson scheme is used for the numerical solution of diffusion terms. The pressure gradient terms are omitted from the equations of motion; pressure gradient-generated flow accelerations are applied after successive over-relaxation determines the pressure field and maintains mass continuity. The model is iterated until it converges to a steady-state solution based on minimal time step change in grid-averaged mean kinetic energy. The number of time steps required depends on the domain size and flow properties; roughly 1000 time steps were required for the simulations here.

### 1.3.5 Lagrangian particle models

The Lagrangian particle approach for simulating dispersal in the boundary layer has many advantages, including less restrictive flow assumptions than Eulerian approaches near the particle source and the potential tracking of individual particles. This overview is designed to describe the model used in this study and relate it to other particle models and relevant statistical concepts. For further reading, helpful overviews are provided by Wilson and Sawford (1996) and Rodean (1996). In addition, an excellent conceptual discussion of time series concepts is provided in Chatfield (2004).

Numerical treatments of turbulent transport may be either Eulerian or Lagrangian. The Eulerian frame of reference is a fixed point, while the Lagrangian approach follows the motion (i.e. particle position is the frame of reference). Within the Eulerian framework, we forecast the change in mean scalar concentration for a specific location due to advective and turbulent diffusive processes. Neglecting horizontal diffusion terms and assuming no local scalar sources, this is expressed as:
Here $s$ represents the mean of the scalar quantity, $u$, $v$, and $w$ are the wind components in $x$, $y$, and $z$ directions, and the primes indicate turbulent components. The first terms on the right hand side represent advection, while the last term represents turbulent diffusion in the vertical direction.

The diffusion term leads to the turbulence closure problem, since the prognostic equation required to define the turbulent flux requires higher order terms (Stull 1988). Closure is required at some level, with higher order terms parameterized. For many applications of numerical weather prediction, the approach is convenient and effective. First order closure yields the following for the vertical turbulent flux of a scalar quantity:

$$
\overline{w's'} = -K \frac{\partial \overline{s}}{\partial z}
$$

Here $K$ is the turbulent transfer coefficient (with units of $m^2 \text{s}^{-1}$), which is physically related to turbulent kinetic energy and length scale (greater turbulence and larger eddies lead to greater mixing and vertical transport).

We may ideally apply this Eulerian approach in the case of particle transport as well, treating the particles as a tracer with a given concentration (with some adjustment for the terminal velocity). Unfortunately, this gradient transport relationship is valid only when the scale of the gradient is greater than the turbulent mixing scale. This assumption is clearly violated near the source (Lamb et al. 1975). For near-source concentrations, of primary interest in problems such as pollen dispersal, this approach is not adequate since the scale of
the near source gradient changes over a much smaller scale than the characteristic turbulent eddy scale.

The Lagrangian approach avoids the near-source closure problem, since the frame of reference is the fluid element itself (note that the closure problem remains in determining the flow fields used to drive the dispersion models). In the Lagrangian framework, the mean concentration is defined (Lamb, et al., 1975) as:

\[
C(x,t) = \int_{-\infty}^{t} Q(t') p(x,t;x_0,t') dt'
\]

(13)

Here \(C(x,t)\) is the mean concentration, \(Q(t')\) is source strength and \(p(x,t;x_0,t')\) is the position PDF (probability density function) that describes the distribution of particles from source \(x_0\) released at time \(t'\) found at time \(t\), location \(x\). The problem remains to determine \(p\). In practice, it is un-measurable due to the large number of particles that require tracking (Lamb, 1975). Following the approach of Taylor (1921), assumptions (i.e. Gaussian, isotropic, stationary) may be used to generate analytical models that describe plume spread (as discussed in Phillip, 1968; Haugen, 1966; Hall, 1975; Draxler, 1976). The analytical approach is problematic in cases with a spatially varying Lagrangian time scale or non-homogeneous turbulence, which motivates the use of numerical solutions (Hall, 1975).

With Lagrangian particle dispersion models (LPD), individual particles are simulated using a random flight model. The plume (pollen cloud in our application) is subsequently represented as an ensemble of stochastic particles. This approach to particle motion makes implicit use of several important statistical concepts. Here I explore these concepts intuitively, with particle velocity as the variable of interest. The marked particle motion in all random flight models follows a stochastic (i.e. random) process.
In the simplest possible model, we have:

\[ u(t) = \varepsilon(t) \]  

(14)

Here \( \varepsilon \) is a random component, which we may specify as Gaussian with independent increments. This model is rather limited, since the real wind is not independent for short time increments. For illustration of this simple case, consider a simulation of the u component of the wind, with a new \( u(t) \) every second. For this simulation, the mean u component is proscribed as 0, with a variance of 1 m s\(^{-1}\). The resulting time series of \( u \) (Figure 1.2) appears random, with uncorrelated increments.

Although the particle velocity looks random, the resulting particle path (Figure 1.1) follows non-stationary random walk behavior, with a slow evolution in particle position (since the particle path is the integrated result of the random shocks). In reality, the particle velocity will not be independent for a small time increment. Given a wind gust at the present time, we know quite a bit about the likely wind speed 0.1 seconds later. In physical terms, the characteristic scale of eddies is large enough that very nearby locations in time and space will be have similar flow characteristics. In statistical terms, the temporal dependence may be expressed through autocorrelation. We can also assume that the wind will de-correlate completely given a large enough time increment, as noted by Taylor (1921).

We adjust for this autocorrelation by expanding equation 14 into a first order autoregressive process (AR), with lag 1 correlation coefficient \( \alpha \).

\[ u(t) = \alpha u(t-1) + \varepsilon(t) \]  

(15)

Now the process carries some memory through \( \alpha \) (which varies from -1 to 1, but must physically be positive in our application). As \( \alpha \) increases, the series looks less and less
random and becomes a random walk at \( \alpha = 1 \) (with a random walk, the independent shocks are integrated and the series has substantial low frequency variability). To demonstrate, simulations were performed using the same random series as before, with \( \alpha = 0.3, 0.6, \) and \( 0.9 \) (Figure 1.3). These are reasonably realistic velocity time series, with the “best” alpha being a function of both time increment and the structure of the turbulence.

We have implicitly made the Markov assumption, in that our variable depends on the previous time step, but not earlier times. This does not mean that our variable at lags greater than 1 will not correlated (see Figure 1.4). The functional dependence, however, is entirely through nearest neighbors. The autocorrelation at greater lags is solely due to the first order dependence and thus the partial auto-correlation (which accounts for the lag 1 dependence) is insignificant. The simulated series also have different spectra, with increasing red noise as alpha increases (not shown).

The spectra with higher autocorrelation coefficients look most similar to observed turbulence spectra (see Stull 1988 for many examples), but this is sensitive to sampling frequency as well as turbulence characteristics. Realistic spectra include clear separation between the larger scale of turbulence generation and dissipation at small scales. Plotted on a log-log scale, a broad inertial subrange with a \(-5/3\) slope lies in between. As explained in Stull (1988), there is a cascade of energy from larger scales to smaller scales; in the inertial subrange, there is a balance of energy cascade from generation to dissipation scales.

For realistic particle trajectories in the planetary boundary layer, adaptations are required. First, we must determine the properties of \( \varepsilon \). We may assume mean zero and Gaussian form, but we must also determine its variance. In addition, we need an appropriate form of autocorrelation function, which itself must be valid given turbulent flow properties.
The landmark work of Taylor (1921) on turbulent diffusion led the way to Lagrangian particle models, as well as Gaussian plume models. His work explored many of the previous concepts implicitly, with a discussion of continuous and discontinuous cases. With some simplifying assumptions, he illustrated that the diffusion problem is reduced to the velocity autocorrelation. The autocorrelation decays as the time increment increases, with an eventual time lag at which the velocity correlation has disappeared. This is consistent with the Markov property and 1st order AR models (Figure 1.4).

While the early Lagrangian particle approach followed intuitively from 1st order autoregressive processes, the nomenclature was typically different. These papers considered a sub-ensemble of particle velocities at the instant of release, with \( u(t) \) as the velocity at time \( t \) after release with initial velocity \( u_0 \) (Phillip, 1968; Smith, 1968; Reid, 1979). The velocity at time \( t \) was broken into correlated and un-correlated components, with auto-correlation function \( R(t) \) and uncorrelated random component \( u'' \):

\[
    u(t) = u_0 R(t) + u''(t)
\]

This follows directly from equation 14, with \( R(t) \) replacing \( \alpha \) and varying with the turbulent characteristics and simulation time step. Particle motion follows a systematic drift associated with the correlated term and a sub-ensemble dispersal component. Phillip (1968) notes that the growth of variance of particle paths is initially driven by the drift term, with the dispersal term becoming dominant in later periods (similar analysis using Taylor’s diffusion relation is provided in Tennekes, 1979).

The autocorrelation function \( R(t) \) is assumed to be independent of the initial velocity and of exponential form, following Taylor’s work and consistent with Markov processes and
Brownian motion (Smith, 1968). The autocorrelation function and associated Lagrangian timescale ($T_L$) are defined by:

$$R_k(\Delta t) = e^{-\Delta t/T_L}$$  \hspace{1cm} (17)

The exponential form is valid for small time intervals (Hall, 1975) and consistent with inertial subrange relations for the structure function (Tennekes, 1979). Hanna (1979) shows that this approach is approximately valid for both Lagrangian (balloon trajectory) and Eulerian data, while Ley (1982) reported agreement with aerosol data.

While the Lagrangian autocorrelation is required for particle simulations (and is more intuitively related to diffusion), turbulent point measurements provide the Eulerian autocorrelation (Hanna, 1981). The Lagrangian and Eulerian time scales may be assumed to be approximately equal for high Reynolds number flow (Corrsin 1963, Kraichnan 1964), with the difference in the statistics due to sampling (Wilson and Sawford, 1996). As discussed by Csanady (1963), the assumption that Eulerian and Lagrangian autocorrelation functions are equivalent is an extension of the hypothesis that the fixed point temporal wind variances are equal to the variances following the flow. Experiments have shown, however, that the Lagrangian time scale is greater than the Eulerian counterpart (Haugen 1966), with a ratio of ~1.7 in the boundary layer (Hanna, 1981). This is consistent with the spectra described by Gifford (1955), which show a shift to higher frequencies in the Eulerian case.

Several authors (e.g. Sawford 1985; Thompson, 1984; Gifford, 1982; Rodean, 1996) note the Markov chain approach makes implicit use of the Langevin equation of (molecular-scale) Brownian motion, and most recent literature expresses model formulations in this
form. The following is the generalized form, where $d\epsilon$ is a Gaussian white noise process with zero mean and variance equal to the time increment $dt$:

$$du = a \, dt + b \, d\epsilon$$  \hspace{1cm} (18)

This Markov process is continuous in time, but not differentiable. This isn’t problematic in practice, given a non-infinitesimal time step appropriate for time scales greater than the Kolmogorov scale (Pope, 1994). This generalized form is useful, since varying assumptions can be used to build models with different forms of coefficients $a$ and $b$ (an excellent overview is provided in Wilson and Sawford, 1996). The Wiener process treatment of acceleration as uncorrelated white noise, consistent with Brownian motion, is invalid in the boundary layer for very small time scales, for which acceleration is correlated (Sawford, 1985). Consistency with Kolmogorov theory in the inertial subrange and the Lagrangian structure function suggests the following form of $b$, where $\epsilon$ is the turbulent dissipation rate (Rodean, 1991; Wilson and Sawford, 1996):

$$b = \sqrt{C_0 \epsilon}$$  \hspace{1cm} (19)

The Kolmogorov structure function constant $C_0$ is related to the Lagrangian timescale, dissipation rate, and velocity variance. The precise value, however, is unknown (Anfossi et al., 2000; Lien and D’Asaro, 2002). In the inertial subrange, turbulence is assumed isotropic, despite the anisotropic forcing that generated the turbulence on larger scales. The model simulates the effect of eddies using these small isotropic increments as building blocks. Rather than simulating the anisotropic forcing at large scales, the implied large eddy structure is generated using these small increments together with coefficient $a$, which may be expressed in terms of the autocorrelation function or related flow properties. When coupled
with homogeneous, isotropic, and Gaussian turbulence, the form of coefficient $a$ results in a model implementation identical to the Markov chain model described above (as in Gifford 1982).

Turbulence is not typically homogeneous in the vertical, especially near plant canopies. The vertical velocity variance changes with height very close to the surface (even in neutral conditions), leading to problems with particle simulations (Wilson et al. 1981). Simulations in these conditions generate an accumulation of particles in low-turbulence areas, since particles are more likely to move toward low-turbulent regions than away from them (Thomson 1984; Sawford 1985). Legg and Raupach (1982) formulated a correction for this unrealistic drift, and subsequent formulations have since been developed for different flow regimes. The well-mixed condition, requiring that a mixed tracer remain mixed, was proposed by Thompson (1987) and is the most robust criterion for the selection of stochastic model parameters (Wilson and Sawford 1996). The well-mixed condition does not account for turbophoresis generated by the gradient in Lagrangian timescale, but this limitation is important only very near the ground (Wilson 2000).

As discussed in Kas and Durbin (2005), Lagrangian stochastic models can be developed based on Eulerian terms. Models with various assumptions of turbulent flow have been derived via implementation of the Fokker-Planck equation, which was suggested by Obukhov (1959) as an alternative to the Langevin equation and expresses the particle position probability density function in terms of Eulerian moments (Rodean 1996; Thomson 1987; Wilson and Sawford 1996; van Dop et al. 1985). The uniqueness problem arises because the well-mixed condition enforces no dynamical content; as a result, multiple models meeting the well mixed condition may produce different dispersive behavior given the same
flow properties (Reynolds 2002). A unique well-mixed 3D solution exists for stationary, homogeneous, Gaussian turbulence that is equivalent to the Markov chain model above. For inhomogeneous turbulence, a unique model similar to Legg and Raupach (1982) exists, but this is not the case in 2D or 3D. With other assumptions, valid models are not often unique, although a unique model does exist for the non-stationary, isotropic, homogeneous case (for discussions of uniqueness see Wilson 2000; Wilson and Sawford 1996; Kurbanmuradov and Sabelfeld 2000; Sawford 1986).

The approach used here follows McNider (1981) and McNider et al. (1988), which is a 3D extension of the Markov chain model above and includes the Legg and Raupach drift correction term in the vertical. Hsieh et al. (1997) found that while the Legg and Raupach drift correction term did not strictly uphold the well-mixed condition, simulations were not sensitive to specific drift correction formation. With maize pollen dispersal simulations, this is not problematic since the relatively heavy particles will not remain suspended near the ground or top of the model domain.

The particles in the model developed here move each time step via mean and turbulent flow components, with the position of the \( i^{\text{th}} \) pollen grain at a time \( \Delta t \) in the future being predicted from its position and velocity at the present time according to:

\[
x_{ik}(t + \Delta t) = x_{ik}(t) + \Delta t\left[u_{ik}(t) + u_{ik}'(t)\right] \quad k = 1,2,3
\]

(20)

\[
u_{ik}'(t + \Delta t) = u_{ik}'(t) R_{ik}(\Delta t) + u_{ik}''(t), \quad k = 1,2,3
\]

(21)

where \( x_k \) is the particle position in direction \( k \), \( u_k \) are mean wind components and \( u_k' \) are Lagrangian turbulent velocity fluctuations. The autocorrelation term \( R \) provides memory of
the particle velocity at the previous time, while \( u_k'' \) is a new random Gaussian turbulent component with mean zero:

\[
u_k'' = \gamma \sigma_k (1 - R_k^2 (\Delta t))^{1/2}, \quad k = 1, 2, 3
\]  

(22)

Here \( \gamma \) is a unit random deviate. The effect of the Eulerian turbulence enters here; greater turbulence (i.e., larger \( \sigma_k \)) will generate random components of larger magnitude, and thus larger particle velocity fluctuations. The Lagrangian timescale \( (T_L) \) is determined by the following, where \( z \) is particle height:

\[
T_L = \frac{0.5 z}{\sigma_k} = \frac{2\sigma_w^2}{C_w \epsilon}
\]  

(23)

The drift correction term follows Legg and Raupach (1982), with the term \( w_c \) subsequently added to the term for vertical position (eq. 21, with \( k=3 \)).

\[
w_c = T_L \frac{\partial \sigma_w^2}{\partial z} \left[ 1 - \exp \left( -\frac{\Delta t}{T_L} \right) \right]
\]  

(24)

In addition to this drift correction, we account for the settling velocity by superimposing the gravitational settling velocity onto the vertical component of the particle’s motion (as utilized for maize pollen dispersion in Aylor et al. 2006, 2003). Wilson (2000) finds this approach to be adequate in most circumstances compared with more complex inertia-particle approaches. The Lagrangian timescale is much larger than the inertial particle timescale except very close to the ground.

With the drift correction and gravitational settling \( (v_i) \), equations 20 and 21 become:

\[
x_{ik} (t + \Delta t) = x_{ik} (t) + \Delta t \left[ u_{ik} (t) + u_{ik}' (t) - \delta_{ik} v_T \right], \quad k = 1, 2, 3
\]  

(25)
\[ u_{ik}'(t + \Delta t) = u_{ik}'(t) R_{ik}(\Delta t) + u_{ik}'(t) + \delta_{ij} w_c, \quad k = 1, 2, 3 \]  

(26)

where \( \delta_{ij} \) is the Kronecker delta (\( \delta_{ij} = 1 \) for \( i=j \); otherwise \( \delta_{ij} = 0 \)).

Since heavy particles are unlikely to precisely follow fluid particle paths, they can fall out of an individual eddy so that the resulting de-correlation is faster than with a fluid element (Csanady 1963). The Lagrangian timescale for these heavy particles must be adjusted, since the particles will lose memory faster than the flow itself (Csanady 1963; Sawford and Guest 1991). Following Wilson (2000) and Li and Taylor (2005), the particle Lagrangian timescale is specified as

\[ \Gamma_p = \frac{\Gamma_L}{\sqrt{1 + (\beta v_t / \sigma_w)^2}} \]  

(27)

where \( v_t \) is the gravitational settling velocity and the dimensionless coefficient \( \beta \) is set to 1.5.

The meteorological input data required by Lagrangian particle models are flexible; data can be taken from atmospheric analysis, numerical models, or field observations. In the first paper, single point field measurements are used with scaling relationships in the surface layer to generate wind profiles over the domain. In papers two and three, the Wang and Takle shelterbelt model provides flow fields for the LPD. In these papers, we explore the impact of the maize field and border on the flow and subsequent dispersion. We also explore the sensitivity of the simulated dispersion to model configuration, including the Lagrangian drift correction and correction for the particle Lagrangian time scale.
1.4 Figures

Figure 1.1 Simulated u component of the wind and pressure perturbation at a height of 2.5 m, for the case of westerly flow and a single 3.5 m tall, 4 m wide border at x = 120 m.
Figure 1.2 Simulated random Gaussian u (m/s) series and resulting evolution in particle position.
Figure 1.3. Simulated 1\textsuperscript{st} order AR \(u\) (m/s) series for \(\alpha=0.3, 0.6, 0.9\).
Figure 1.4. Autocorrelation function (ACF) for simulated 1st order AR $u$ (m/s) series for $\alpha=0.3, 0.6, 0.9$. The ACF values correspond to the correlation of $u_i$ with $u_{i+n}$, where $n$ indicates the lag.
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CHAPTER 2. LAGRANGAIN NUMERICAL SIMULATIONS OF CANOPY AIR FLOW EFFECTS ON MAIZE POLLEN DISPERsal

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2.1 Abstract

A three-dimensional Lagrangian random flight model was constructed for numerical simulations of maize pollen dispersion. The model simulates the path of tracer particles which are interpreted as individual pollen grains, with particle motion determined by the mean flow and a stochastic turbulent velocity. The Lagrangian approach was chosen because it can be extended to complex flow regimes. The capacity of the model to simulate measured patterns of pollen deposition was tested by comparing simulations to measurements for a small maize canopy isolated within a large field of soybeans near Ames, Iowa, USA in August 2003. For this application, measurements from a single point meteorological observation were used to generate a surface layer wind profile over the maize canopy and surrounding soybean field. The method used to construct the wind field included development of internal boundary layers as the airflow passed from one canopy surface to

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another. The dispersion model produced spatial patterns of particle deposition that included the sharp near-source deposition gradient consistent with observations. The model tended to over-predict particle deposition near the source field and under-predict deposition at greater distances. Inclusion of the effect of the roughness difference between the maize canopy and the surrounding soybean canopy on the flow field was found to be essential for simulation accuracy. Agreement with observations improved considerably by including an approximation for vertical motions induced by changes in surface cover. These results indicate that the Lagrangian random flight model provides a realistic simulation of pollen dispersal from an isolated maize canopy. A more complete hydrodynamic model should be explored to better represent the influence of surface inhomogeneities on the flow field.

Keywords: Maize; Pollen; Modelling; Microclimate

2.2 Introduction

Use of genetically modified (GM) maize has stimulated interest in the analysis and prediction of pollen dispersion, since the open pollination of maize introduces the possibility of outcross and conflicts with the need to limit genetic drift. Unintended spread of GM pollen into organic or conventional varieties may have trade or legal consequences (Jemison and Vayda 2001; Aylor et al. 2003). There is also concern that GM maize may outcross with wild relatives (Garcia et al. 1998).

Current knowledge is insufficient to predict the level of out-crossing accurately. Quantitative assessment must consider both crop biological processes and pollen transport in the atmosphere (Aylor et al. 2003; Ireland et al. 2006). Out-crossing requires that
adventitious pollen out-compete local pollen; local pollen density, genetic factors, and environmental factors influence the outcome of this competition. Westgate et al. (2003) found field-scale pollen shed occurred over a 10 to 12 day period and peaked 2 to 3 days after anthesis. Typical plants produced 3 to 5 x 10^6 pollen grains each and maximum kernel set required pollen shed of about 3000 pollen grains per exposed silk. Kernel set decreased significantly with reduced pollen shed; thus, the risk of outcross may increase if the local pollen supply is too small to out-compete pollen from remote sources.

Once pollen is shed, local meteorology determines its dispersal, with greater wind speeds and greater turbulence promoting dispersal to longer distances. Maize pollen has a large diameter (70 to 100 µm) and thus a large settling velocity (20 to 30 cm s^{-1}). As a consequence most pollen is deposited inside the source field and deposition decreases rapidly with distance from the source. Raynor et al. (1972) found that roughly twice as much pollen fell inside the source field as outside it, while Loubet et al. (2002) found that maximum deposition occurred within 1 to 3 m of the source field. In a study of maize pollen deposition onto milkweed, Pleasants et al. (2001) found average deposition of about 170 grains cm^{-2} inside the source field and 14 grains cm^{-2} outside the field. Jarosz et al. (2003) found that deposition rates at 32 m from the source field were less than 10% of those at 1 m and that 99% of emitted pollen was deposited within 30 meters of the source field. These deposition patterns imply that pollination is most often attributable to a nearby source, consistent with findings that 50% of the kernels of an individual plant result from pollen released within a 12 m radius (Emberlin et al. 1999).

Despite these findings, low levels of maize out-crossing and maize pollen deposition have been observed at distances several hundred meters from the pollen source (Ireland et al.
Aylor et al. (2003) showed that the commonly-assumed exponential decay of deposition with distance was not an adequate fit to published out-cross data. They showed that the pattern of dispersion away from the source resembled a "long tail" following a power-law relation consistent with theoretical aspects of turbulent dispersion. An implication of their result is that small amounts of pollen could be expected to travel large distances from the source. Brunet et al. (2003), using measurements taken by aircraft, found viable pollen through the entire depth of the atmospheric boundary layer. Their results imply that updrafts due to turbulent eddies in the boundary layer can overcome the terminal fall velocity of maize pollen grains and transport pollen to considerable heights (hundreds of meters or more), so that pollen could travel long distances before settling to a receptor.

Jarosz et al. (2003) analyzed vertical flux of maize pollen downwind of a source field at a height of 3 m. They separated the flux into convective, diffusive, settling, and turbophoretic components. The settling flux was caused by gravitational settling, while the convective flux was associated with the mean vertical velocity caused by roughness changes. Roughness changes induce vertical velocities with upward motion expected near smooth to rough transitions (owing to horizontal flow convergence) and subsidence near rough to smooth transitions (owing to horizontal flow divergence). The turbulent diffusive flux was positive, since the height of analysis was above the canopy. The smaller counter-gradient turbophoretic flux is difficult to assess, but responds to the gradient of turbulent kinetic energy (Wilson 2000). The results of Jarosz et al (2003) indicate that dispersal is affected by the relative magnitudes of several processes. Some of these processes (such as the
convective flux) are strongly affected by variations in canopy aerodynamics so that methods developed for uniform land cover may not be appropriate for nonuniform conditions.

Numerous modeling approaches to the problem of seed and pollen dispersal have been developed. Broadly, these can be classified as empirical fits to observed data, mechanistic models, or some combination of the two. An example of an empirical fit to observations for the case of maize outcrossing is given by Goggi et al. (2006). Klein et al. (2006) modeled the dispersion of pollen from oilseed rape using individual dispersion functions (IDF), also known as dispersal kernels. They found that extrapolation of measured results to long distances was sensitive to the functional form adopted for the IDF, and that the best fit to observations was obtained using a power-law type of function. Klein et al. (2003) used a quasi-mechanistic approach in which physical and biological considerations were used to develop a model framework that was subsequently fit to observed data. Their quasi-mechanistic model included such physical influences as wind speed and Brownian motion, and such biological factors as the height difference between male and female flowers.

The simplest mechanistic models predict straight-line trajectories using a single wind speed during the trajectory (Greene and Johnson 1996; Nathan et al. 2001). While this approach has the advantage of relative simplicity, it is less suitable for long-range dispersal (as noted by Nathan et al. 2002). Bullock and Clarke (2000) compared seed data with the Greene and Johnson model and with exponential and power law empirical models, concluding that the dispersive tail was underestimated in each case. Tackenberg (2003), using a trajectory model, concluded that unstable conditions with light winds promoted dispersal. Soons et al. (2004) questioned this result, due to its use of a single point vertical velocity observation with generally upward vertical velocities (which would be location
specific). They further noted that strong turbulence associated with greater wind speeds will produce greater dispersal distances when modeled with realistic turbulent vertical velocity autocorrelation. Some other mechanistic models have adopted Gaussian plume methods, which have a long history in simulating air pollution dispersion. Ireland et al. (2001) applied a widely-used Gaussian plume model, the EPA Industrial Source Complex Dispersion model, to simulate the transport of pollen from maize fields. Loos et al. (2003) extended the Gaussian plume approach by use of localized near field theory.

Several studies of pollen dispersal have used Lagrangian random flight simulations (Di-Giovanni et al. 1995; Aylor et al. 2003; Jarosz et al. 2004). The Lagrangian approach has also been used in related dispersion applications, such as the dispersal of glass beads (Wilson, 2000), seeds (Nathan et al., 2002), and spores (Aylor and Flesch, 2001). Lagrangian approaches by definition adopt a frame of reference that moves with the material being transported. This contrasts with Eulerian approaches, which adopt a fixed frame of reference through which the material moves. Applications of Lagrangian methods to pollen dispersion use a large (at least several thousand) ensemble of virtual particles which in the case of pollen dispersion are interpreted as a stochastic sample of the actual pollen released from a source. Lagrangian methods are versatile; for example, they can be applied to complex topography, as long as the characteristics of the flow are known or can be simulated accurately. The Lagrangian approach also enables tracking of individual model particles as they travel from source to receptor. Aside from simplifying source-receptor relationships compared to Eulerian methods, environmental influences on the particle can be incorporated along the particle trajectory.
Previous Lagrangian particle models for maize pollen dispersion have been implemented in two dimensions (height by one horizontal dimension; e.g., Jarosz et al. 2003, Aylor et al. 2006). In the present study we extended the Lagrangian approach to three dimensions and evaluated model simulations against observations. We also explored the sensitivity of model predictions to details of the dispersion methodology and to meteorological conditions.

2.3 Materials and methods

2.3.1 Lagrangian dispersion model

Computational approaches for transport of material in fluids may be either Eulerian (frame of reference is fixed) or Lagrangian (frame of reference follows the motion). In the Lagrangian framework, the mean concentration is defined (Lamb et al. 1975) as:

\[
C(x, t) = \int_{-\infty}^{t} Q(t') p(x, t; x_0, t') dt'
\]

(1)

Here \(C\) is the mean concentration, \(Q\) is source strength and \(p(x, t; x_0, t')\) is the position probability density function (PDF) that describes the distribution of particles released from source \(x_0\) at time \(t'\) that are later found at location \(x\) at time \(t\). The main challenge is to determine \(p\). In practice, \(p\) is not directly measurable due to the large number of particles that require tracking (Lamb 1975). Following the approach of Taylor (1921), assumptions regarding the statistical properties of turbulent eddies may be used to generate analytical models that describe plume spread (Haugen 1966; Hall 1975; Draxler 1976). The analytical approach is problematic in cases with a spatially varying Lagrangian time scale or nonhomogeneous turbulence, which motivates the use of numerical solutions (Hall 1975). In
the present application we adopt a numerical solution technique owing to its greater
generality.

Particle motion is defined by two terms: a systematic drift associated with the
correlated term, and a sub-ensemble dispersal term. Philip (1968) notes that the growth of
variance of particle paths initially is dominated by the drift term, with the dispersal term later
becoming dominant. A similar analysis using Taylor’s diffusion relation is provided by
Tennekes (1979). The autocorrelation function is assumed to be independent of the initial
velocity and of exponential form, following a Markov chain process and Brownian motion
valid for stationary homogeneous flow (Smith 1968; Hall 1975). The exponential form is
valid for small time intervals and is consistent with inertial subrange relations for the
structure function (Tennekes 1979). Hanna (1979) confirmed that the first-order Markov
approach is approximately valid for both Lagrangian (balloon trajectory) and Eulerian data,
while Ley (1982) reported agreement with aerosol data.

Several authors (e.g., Legg and Raupach 1982; Sawford 1985) have noted the Markov
chain approach makes implicit use of the Langevin equation of molecular-scale Brownian
motion, and most recent literature discusses model formulations from this perspective. The
generalized form is

\[ du = a \, dt + b \, d\epsilon \]  

(2)

where \( d\epsilon \) is a Gaussian white noise process with zero mean and variance equal to the time
increment \( dt \). This generalized form is useful since varying assumptions can be used to build
models with different forms of coefficients \( a \) and \( b \) (an excellent overview is provided in
Wilson and Sawford 1996). Consistency with Kolmogorov theory in the inertial subrange
gives
where $\varepsilon$ is the turbulent dissipation rate and $C_0$ is a constant. Coefficient $a$ is interpreted as the conditional mean acceleration (Wilson and Flesch 1997) and its implications have been discussed in considerable detail elsewhere (Thomson 1987; Wilson and Sawford 1996; Schwere et al. 2002).

Boundary-layer turbulence often is not homogeneous in the vertical dimension. Particles are more likely to move into low-turbulence regions than out of them, leading to spurious accumulation of particles in low-turbulence areas. This accumulation violates the well-mixed condition, which requires that a mixed tracer remain mixed. Legg and Raupach (1982) formulated a correction for this unrealistic drift, and subsequent formulations have since been developed for different flow regimes. The well-mixed condition as proposed by Thomson (1987) has become the most robust criterion for the selection of stochastic model parameters (Wilson and Sawford 1996).

The approach used here is a three-dimensional implementation of the Markov chain model described above and includes the Legg and Raupach (1982) drift correction term in the vertical dimension. The particles move via mean and turbulent flow components, with the position of the $i^{th}$ particle at a time $\Delta t$ in the future being predicted from its position and velocity at the present time $t$ according to:

$$x_{ik}(t+\Delta t) = x_{ik}(t) + \Delta t\left[u_{ik}(t) + u'_{ik}(t)\right], \quad k = 1, 2, 3 \quad (4)$$

$$u'_{ik}(t+\Delta t) = u'_{ik}(t) R_k(\Delta t) + u''_{ik}(t), \quad k = 1, 2, 3 \quad (5)$$
where $x_{ik}$ is the particle position in each spatial dimension $k$; $u_{ik}$ are mean wind components and $u_{ik}'$ are Lagrangian turbulent velocity fluctuations. (Three dimensionality is indicated by the spatial index $k = 1, 2, 3$.) The autocorrelation $R$ provides memory of the particle velocity at the previous time, while $u_{ik}''$ is a random Gaussian turbulent perturbation:

$$u_{ik}'' \sim \gamma \sigma_k \left[ 1 - R_k^2(\Delta t) \right]^{1/2}, \quad k = 1,2,3 \quad (6)$$

Here $\gamma$ is a unit random deviate and $\sigma_k$ is the standard deviation of turbulent velocity fluctuations in spatial dimension $k$. Greater turbulence (larger $\sigma_k$) produces random components of larger magnitude, and thus larger particle velocity fluctuations. The autocorrelation function

$$R_k(\Delta t) = \exp(-\Delta t / \Gamma_p) \quad (7)$$

depends on the particle Lagrangian timescale $\Gamma_p$, which is derived from the fluid Lagrangian timescale $\Gamma_L$:

$$\Gamma_L = 0.5 \frac{z}{\sigma_w} = \frac{2\sigma_w^2}{C_0 \epsilon} \quad (8)$$

Here $z$ is height and $C_0$ is a dimensionless coefficient. For heavy particles, the Lagrangian timescale must be adjusted since the particles will lose memory faster than the flow itself (Csanyi 1963; Sawford and Guest 1991). Following Wilson (2000) and Li and Taylor (2005), the particle Lagrangian timescale is specified as

$$\Gamma_p = \frac{\Gamma_L}{\sqrt{1 + (\beta w_g/\sigma_w)^2}} \quad (9)$$

where the dimensionless coefficient $\beta$ is set to 1.5. As the settling velocity $w_g$ approaches zero (e.g., for very small particles), $\Gamma_p$ approaches $\Gamma_L$. 
The drift correction term $w_c$ follows Legg and Raupach (1982):

$$w_c = \Gamma_L \frac{\partial \sigma_{w}}{\partial z}[1 - R_3(\Delta t)] \quad (10)$$

In addition to the drift correction, we account for gravitational settling by superimposing the terminal fall speed $v_T$ onto the vertical component of the particle’s motion (as used for maize pollen dispersion by Aylor et al. 2003). With these modifications equation (4) becomes:

$$x_{ik}(t+\Delta t) = x_{ik}(t) + \Delta t[u_{ik}(t) + u'_{ik}(t) + \delta_{k3}(w_c + v_T)], \quad k = 1,2,3 \quad (11)$$

where $\delta$ is the Kronecker delta.

### 2.3.2 Meteorological input data

The dispersion model employed here is designed to be flexible in terms of its source of meteorological input for wind and turbulence. Meteorological data may in principle be taken from atmospheric analyses, results of atmospheric models, or observations. Hence we have chosen to separate the generation of meteorological input from the workings of the Lagrangian dispersion model *per se* both in terms of the structure of the model code and in our present discussion. The simulations reported here used near-surface weather data from a single station near the maize field, which is typical of a data available in practical settings. Wind and turbulence profiles were subsequently generated for the surface layer using the single-station observations and crop characteristics.

The mean flow above the canopy is generated using the single point observed data and surface layer similarity theory:

$$\frac{\partial u}{\partial z} \frac{kv}{u_*} = \phi_m(\frac{z}{L}) \quad (12)$$
Here $u_*$ is the surface friction velocity and $\phi$ is the non-dimensional wind profile, which is a function of height $z$ and the Monin-Obukhov length $L$:

$$L = \frac{-\rho c_p T_{\text{ref}} u_*^3}{k g H}$$  \hspace{1cm} (13)

where $\rho$ is density, $c_p$ is the specific heat for dry air, $T_{\text{ref}}$ is the reference temperature (taken as the observed hourly-mean surface temperature), $k$ is the von Karman constant (0.41), $g$ is the gravitational acceleration (9.8 m s$^{-2}$), and $H$ is surface sensible heat flux.

Standard deviations of the wind components above the canopy follow conventional scaling for the atmospheric surface layer, as summarized in Garratt (1992):

**Unstable or neutral stratification:**

$$\sigma_u = \sigma_v = u_* \left(12 - 0.5 \frac{h}{L}\right)^{\frac{1}{3}}$$  \hspace{1cm} (14a)

$$\sigma_w = 1.25 u_* \left(1 - 3 \frac{z}{L}\right)^{\frac{1}{3}}$$  \hspace{1cm} (14b)

**Stable stratification:**

$$\begin{cases} 
  \sigma_u = \sigma_v = 2.29 u_* \\
  \sigma_w = 1.25 u_* 
\end{cases}$$  \hspace{1cm} (14c)

where $u$, $v$ are the horizontal components of velocity and $w$ is the vertical component. The simulations presented here assumed a boundary layer depth $h = 500$ m, which is typical of values during mid-morning when pollen shed usually is most intense. Tests showed little sensitivity to $h$ within reasonable ranges for summertime mid-morning values.

Physical characteristics of the canopy significantly alter the mean and turbulent flow within and just above the canopy (Raupach and Thom 1981; Raupach et al. 1996; Finnigan 2000). Despite the complexities of canopy flow, several approaches generate a reasonable
mean canopy wind profile (Raupach and Thom 1981). Our approach follows Cionco (1972) in which wind speed is determined by the height within the canopy \((z)\), the wind speed at the top of the canopy \((U_h, \text{ with } h_c \text{ as the canopy height})\), and an attenuation coefficient \((\alpha)\):

\[
U_z = U_h \exp[\alpha (z/h_c - 1)]
\]  

(15)

Cionco (1972) found this formula valid for several canopy types, ranging from agricultural crops to Christmas trees. The attenuation coefficient \(\alpha\) is a function of vegetation density, which varies with crop type and growing stage. We used \(\alpha = 4\) following measurements for a mature maize canopy by Wilson et al. (1982). Sensitivity tests (not shown) displayed negligible sensitivity of pollen deposition to the choice of attenuation coefficient over a range of values reported in the literature.

The roughness sub-layer, which extends to \(2(h_c-d)\) above the displacement height \((d)\), is a layer in which eddy diffusivities are enhanced and gradients are reduced (Cellier and Brunet 1992; Molder et al. 1999; Mahrt 2000). Our approach for the mean flow in the roughness sublayer follows Cellier and Brunet (1992), in which the inertial surface layer wind profile is adjusted for the canopy roughness and closure. The change in \(u\) as \(z\) increases from \(z_1\) to \(z_2\) is

\[
u(z_2) - u(z_1) = (u \cdot \eta) \left\{ [(z_2/z_r)^{\eta} - (z_1/z_r)^{\eta}] / \eta - \psi_{h}^{*} (z_2/z_r, z_2/L) + \psi_{h}^{*} (z_1/z_r, z_1/L) \right\}
\]  

(16)

where the top of the roughness sublayer is \(z_r\) and \(\psi_{h}^{*}\) is a stability correction term. The coefficient \(\eta\) varies with canopy type, with \(\eta\) approaching unity for very dense canopies (Cellier and Brunet 1992 found 0.45 for maize). The standard deviations of the wind components are also altered within the roughness sublayer. Following Aylor and Flesch (2001), the values decrease linearly in the roughness sublayer, with a 15% reduction from the
surface layer value at the canopy top. Inside the canopy, the adjustment follows Wilson (2000).

\[ \sigma_{(u,v,w)} = \sigma_{\text{ref}} \left( 0.2 + 0.8 \frac{z}{h_c} \right) \]  

(17)

Internal boundary layers form as flow in equilibrium with one surface type passes over a surface with different characteristics, often with a sudden step change (Rao et al. 1974; Klipp and Mahrt 2003). As air passes over the new surface, the internal boundary layer grows deeper until the surface layer is in equilibrium with the new surface properties. Our model includes internal boundary layer adjustments following an adaptation of the approach described in Savelyev and Taylor (2003) in order to account for the transition of flow regimes between the maize field and the surrounding soybean canopy. The main effect of this adjustment is a decrease in low-level wind speed over the maize canopy relative to that over the soybean canopy.

2.3.3 Field data

Predicted pollen dispersion was compared with observations from a field experiment near Ames, Iowa on 6 through 12 August 2003. The source field was 100 m x 90 m of a commercial maize hybrid planted at approximately 7 plants m\(^{-2}\) and was surrounded by a field of soybeans. The maize canopy was approximately 2.2 m high and the soybean canopy was approximately 1 m high.

Pollen was collected daily on sticky traps at 136 locations approximately 1, 10, 135, 100, 150, 200, and 250 m from the source field in the N, NW, E, SE, S, SW, W, and NW directions, along with 12 equally spaced receptors inside the source field (Figure 2.1). The traps were deployed around sunrise and removed in the early evening (around 18:00 local
time). A new set of traps was deployed on each day. Traps were placed within the source field and in the surrounding soybean field on stands at approximately 1.2 m above the ground, which is near apical ear level. The number of pollen grains on each trap was counted in the laboratory using fluorescence microscopic imaging and automated image analysis software. Details and specific materials for both the field measurements and imaging analysis are given by Fonseca et al. (2002). Results are shown here for 8, 9, 10 and 11 August, which encompasses the period of peak pollen shed for the source field.

Two portable weather stations were deployed during the experiment, one near the north edge of the maize field and the other near the south edge. Each station was located just outside of the maize source about 2 m into the surrounding soybean field. The stations were identically configured with Campbell Scientific model 05305 WindMonitor AQ propeller anemometers. Winds were sampled at 15 second intervals using a Campbell Scientific model CR10X data logger and the samples were averaged over hourly periods. We used data from the station that was upwind in the sense of the hourly-average wind as input for the meteorological analysis. Hourly observed wind data summarized using wind roses for each day (Figure 1.2).

2.4 Results

Wind and turbulence data were generated on a discrete three-dimensional grid. Grid spacing was 2 m in both the \( x \) and \( y \) dimensions; vertical spacing was 0.2 m near the ground and increased by a factor of 1.1 for each level up to the domain top at 60 m (no particles were found to reach the top of the domain). The time step in the Lagrangian particle model was \( \Delta t = 0.5 \) s. The particle model was run for each hour during the day using the meteorological
analysis applied to the wind observation that was upwind from the maize field. The model continually released virtual pollen grains at a height of 2.2 m during the course of each simulation, with a total of 432,200 virtual pollen grains released in each hourly simulation. A uniform area source was approximated by using 2161 source locations spaced evenly throughout the maize field, corresponding to each point of the 2x2 m horizontal grid. Results for each day were compiled by summing the individual hourly simulations, weighting each hour using an idealized pattern of diurnal pollen shed peaking in late morning (Westgate, unpublished). Owing to computational limitations, the number of simulated particles was only a small sample of the actual number of pollen grains shed. For example, the peak simulated pollen deposition on 10 August was 51 pollen grains per m$^2$, while the peak observed deposition for that day was $6.97 \times 10^6$ pollen grains per m$^2$. Thus the ratio of the number of simulated pollen grains to the number observed was on the order of $10^{-5}$ to $10^{-6}$.

To simplify comparisons between predicted and observed values both were scaled to a maximum of 100.

Spatial patterns of accumulated daily observed (Figure 2.3) and simulated (Figure 2.4) deposition are broadly similar. Simulated deposition patterns captured some of the details of the observed spatial distribution such as the two lobes of deposition on the east side of the source field observed on 8, 9 and 11 August. The simulated deposition patterns tended to be smoother and more uniform than the observed patterns. Two aspects of the model formulation may produce a smoother simulated pattern than observed. First, we assume that pollen release is uniform across the source field, whereas actual fields often develop non-uniformly owing to small differences in plant development associated primarily with soil characteristics. The resulting nonuniformity in the spatial pattern of pollen shed leads to
nonuniformity in pollen deposition, all else being equal. Second, we assume that pollen release follows the same diurnal trend on each day independent of weather characteristics or other influences. Since wind speed and direction vary somewhat throughout the day, sub-daily correlation between pollen shed and meteorology (e.g., wind gusts that shake pollen loose from the anthers) could produce inhomogeneous patterns of pollen deposition. At present, relationships between pollen shed intensity and meteorological conditions are not sufficiently well-known to account for such effects quantitatively. The difference between the observed and simulated deposition (Figure 2.5) shows that the model tends to deposit too much pollen near the field edges, especially the upwind or lateral edges.

Downwind transects for each day (Figure 2.6) show that the model captured the sharp gradient of deposition near the source but deposition at greater distances tended to be under-predicted. An exception is 10 August, when the model substantially over-predicted pollen deposition immediately downwind from the source field and under-predicted deposition at greater distances. The observed pollen in this transect peaks at 11% of the field maximum 1 m from the field, while model deposition peaks at 77% of the field maximum. Reasons for the poorer agreement on 10 August than other dates tested are not clear. Winds on this date were generally weaker and more variable than on the other dates, so that the effect of turbulent convective mixing may have been relatively large in relation to transport by the mean wind. The large error at some near-field locations may be due in part to the assumption of uniform pollen production throughout the field. Nonuniformity of pollen shed near the field edge could result in especially large errors, as deposition values fall dramatically with distance near the source field.
The model results indicated little or no pollen deposition occurred 100 m or more
downwind of the source field, which was generally consistent with observations (Figure 3).
In three cases, however, very low levels of pollen deposition were observed at such
distances. The relatively limited total number of simulated particles results in a very small
probability that nonzero deposition will be simulated at locations far from the source. As
noted previously, if we interpret the simulated particles as a sample of the actual pollen cloud
then the ratio of simulated particles to pollen grains in the field is of order $10^{-5}$ to $10^{-6}$. The
ratio of observed pollen deposition at far downwind distances to observed pollen deposition
within the source field is of order $10^{-3}$ to $10^{-4}$, suggesting that the number of particles
simulated may have been only marginally adequate. Limited computer power made it
impractical to increase the number of particles simulated substantially. The simulations
reported here each required about 3 hours of computing time, so increasing the number of
particles by one to two orders of magnitude would have required computing time on the
order of days for each simulation. Continuing advances in computational technology will
enable simulations using much greater numbers of particles.

2.5 Sensitivity analysis

2.5.1 Sensitivity to dispersion model formulation

We examined the sensitivity of dispersion model results to drift correction and
Lagrangian timescale adjustment for the 10 August case. We selected this case since the
peak pollen deposition in the source field occurred on this day.
Omission of the drift correction term had only a modest effect on the pattern of pollen dispersal (Figure 2.7). This is likely due to the limited amount of time the pollen is airborne in the domain and the lack of large turbulent gradients in the flow. Omitting the Lagrangian time scale adjustment for particles (Figure 2.7) substantially increased the proportion of simulated pollen grains deposited farther downwind. This result contrasts with that of Aylor and Flesch (2001) who found only a small effect of Lagrangian time scale adjustment on dispersion of *Lycopodium* spores and *Venturia inaequalis* ascospores. The difference in sensitivity reflects the much larger settling velocity of maize pollen (about 0.2 m s\(^{-1}\)) compared to that of *Lycopodium* spores (0.019 m s\(^{-1}\)) and *V. inaequalis* ascospores (0.002 m s\(^{-1}\)). The large settling velocity of maize produces a decrease in the particle Lagrangian time scale (via Equation 9) and consequently a decrease in autocorrelation or "memory" of particle motion. Deleting the time scale adjustment therefore increased the autocorrelation of the turbulent velocity component, so particles that attained large turbulent velocities maintained those velocities and were dispersed across greater distances. Since the number of particles deposited farther downwind increased, agreement of simulated and observed deposition arguably was improved by omitting the time scale adjustment. One possible reason for this result is that wind speeds during the study were generally light (Figure 2.2), and thus approached the free convective limit where the velocity variance no longer scales with friction velocity \(u^*\). We suggest this point be explored further using observations such as sonic anemometry that would permit more direct insight into turbulent statistics.
2.5.2 Sensitivity to local meteorology

Sensitivity experiments showed the simulated pattern of pollen dispersal was moderately sensitive to details of the meteorological inputs. In general, simulated pollen deposition was more sensitive to wind speed than to thermodynamic stability when each was varied over ranges that reflected the uncertainty of the observations. Stability produced a noticeable increase in simulation error only for very unstable conditions, which were introduced by specifying a sensible heat flux of 300 W m$^{-2}$ typical of arid to semi-arid climates (Unland et al. 1996). The large sensible heat flux produced more intense turbulent fluctuations so that pollen traveled much farther than was observed (Figure 8). Removing the adjustments for the effect of the maize canopy on wind and turbulence increased simulation error. When the effect of the maize canopy on air flow was omitted, such that the wind profile was uniform over the entire domain, the low-level wind speed was greater over and downwind from the source field. This led to excessive deposition at all downwind locations except the farthest distance (Figure 2.8). This result indicates that for situations with non-uniform surface cover, inclusion of differential roughness is essential to simulation accuracy.

Jarosz et al. (2004), using a two-dimensional Lagrangian particle approach similar to that of Aylor and Flesch (2001), accurately simulated maize pollen concentration levels but under-predicted pollen deposition near the field. They suggested that simulation error was likely the result of not fully representing the flow regime at the roughness transition at the edge of the field. In light of their findings with regard to the importance of the roughness transition, we extended our meteorological analysis by including an approximation of the effects of convergence and divergence on the vertical component of flow. The decrease of
wind speed as the flow crossed from the soybean canopy to the aerodynamically rougher maize field would be expected to produce flow convergence and upward motions, while recovery of the wind after crossing back over the soybean canopy would be expected to produce divergence and downward air motions. We diagnosed the magnitudes of these vertical velocities according to the incompressible continuity of mass relation,

\[
\frac{\partial w}{\partial z} = -\left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)
\]  

(16)

Jarosz et al. (2004) used a similar approach except they diagnosed \(\partial w/\partial z\) analytically from a polynomial fit for \(u\), while we compute \(\partial w/\partial z\) using finite-difference methods on a computational grid. For smoothly varying flow fields we expect the two approaches to produce nearly identical results. The finite-difference approach is more general, however, because it does not require a functional fit. It is important to note that while Equation 16 preserves continuity of mass, it does not account for dynamic pressure that results from flow perturbations. A full treatment would require solution of a complete nonlinear numerical hydrodynamic model, which is beyond the scope of the present study.

Including convergence-divergence effects on vertical flow velocity resulted in a marked improvement in the correspondence between observed and simulated pollen deposition (Figure 2.9). Deposition within about 50 m of field edge was reduced and deposition at farther distances increased. Diagnosed vertical motions over the field were generally upward (Figure 2.10), causing pollen to be lifted to heights where it was subject to stronger winds and more intense turbulence. Lifting therefore reduces near-field deposition and increases the potential for far-downwind deposition. While these results are
encouraging, we caution that the Equation 16 is a simplification of the complex flow dynamics that are caused by roughness changes.

2.6 Conclusions

A three-dimensional Lagrangian model of maize pollen dispersion has been developed and tested using field data collected in central Iowa during August 2003. The model captured the sharp deposition gradient near the source field. The results include a dispersive tail of low deposition at greater distances, although simulations tended to deposit too much pollen very close to the field. Given that this problem was not systematic for all directional transects, it may be due to a combination of deficiencies in model formulation and inability to include within-field variations in pollen shed. We note further that fully three-dimensional simulations require many more particles than two-dimensional simulations, simply because particles can disperse in a third dimension. We recommend that future three-dimensional simulations (using greater computer power) track larger numbers of particles.

Sensitivity tests revealed that the inclusion of flow effects resulting from differential roughness between the maize canopy and the surrounding soybean field was essential for producing realistic results. Omitting the particle adjustment to the Lagrangian time scale resulted in slightly improved model performance, suggesting that the form of the adjustment may not have been appropriate for the circumstances of our field study.

Agreement between simulated pollen deposition and field observations was improved substantially by including an approximation for vertical motions using the incompressible continuity of mass relation. This result suggests that more detailed representations of the flow should be explored so that the effects of roughness transitions on pollen dispersion can be included in a more complete and physically consistent manner. Specifically, we
recommend that future research should explore the use of three-dimensional hydrodynamic models to produce physically-consistent three-dimensional depictions of the flow. This would make it possible to explore more fully the influence of varying surface cover on maize pollen dispersion and deposition.

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2.8 References


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2.9 Figures

Figure 2.1. Receptor locations during the August 2003 field experiment. The rectangle indicates the source field. The locations were estimated by converting GPS locations to XY coordinates, with \( y = 0 \) at the southernmost location and \( x = 0 \) at the westernmost location.
Figure 2.2. Wind roses constructed each day from hourly wind observations at the upwind surface weather station for each hour. Length of each spoke indicates the percentage of hours on each day with wind from the direction indicated by that spoke. Values at the end of each spoke are mean speed (m s$^{-1}$) when the wind was from the indicated direction. Daily vector mean speed and direction are given at the top of each plot.
Figure 2.3. Logarithm (base 10) of observed pollen deposition on 8, 9, 10, and 11 August 2003, scaled as described in text.
Figure 2.4. Logarithm (base 10) of simulated pollen deposition on 8, 9, 10, and 11 August 2003, scaled as described in text.
Figure 2.5. Simulated minus observed pollen deposition on 8, 9, 10, and 11 August 2003, scaled as described in text. (Values are not logarithms as used in Figures 2 and 3.)
Figure 2.6. Transects in the downwind direction of the logarithm (base 10) of observed and simulated pollen deposition for (a) 8 August, (b) 9 August, (c) 10 August, and (d) 11 August 2003.
Figure 2.7. Transect in the downwind direction of the logarithm (base 10) of observed pollen deposition and of simulated deposition for 10 August with different dispersion model implementations. Solid line, observed deposition; dashed line, control simulation; solid line with triangles, using the fluid Lagrangian time scale instead of the particle Lagrangian time scale (see Equation 9); solid line with squares, omitting the drift velocity correction $w_c$ (see Equation 10).
Figure 2.8. Transects of the logarithm (base 10) of observed pollen deposition and of simulated deposition with different representations for the meteorological analysis. Solid line, observed deposition; dashed line, control simulation; solid line with crosses, assuming a surface sensible heat flux of 300 W m$^{-2}$; solid line with diamonds, neglecting the influence of the roughness difference between the maize field and the surrounding soybeans.
Figure 2.9. Transect in the downwind direction of the logarithm (base 10) of observed pollen deposition and of simulated deposition from the control and from a simulation with vertical motions diagnosed using the incompressible continuity equation. Solid line, observed deposition; dashed line, control simulation; solid line with heavy dots, simulation with diagnosed vertical motions.
Figure 2.10. Velocity vectors from the meteorological analysis with vertical motions diagnosed using the incompressible continuity equation. The vertical component of the velocity vector has been exaggerated by a factor of 10 to aid visualization.
CHAPTER 3. APPLICATION OF A SHELTERBELT MODEL FOR LAGRANGIAN SIMULATIONS OF MAIZE POLLEN DISPERsal

A Paper to be submitted to Field Crops Research

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3.1 Abstract

A shelterbelt flow model has been extended to three dimensions and used to provide the flow field for Lagrangian particle simulations of maize pollen dispersal. In many cases, maize pollen source fields are surrounded by regions with different surface characteristics. This results in complex flows, which are difficult to represent by empirical methods and can have a significant impact on the resulting dispersal. The dispersion model simulates the path of individual pollen grains, with particle motion determined by the shelterbelt model-simulated mean flow and a stochastic turbulent velocity. The capacity of the model to simulate measured patterns of pollen deposition was tested by comparing simulations to measurements for a small maize canopy isolated within a large field of soybeans near Ames, Iowa, USA in August 2003. For this application, measurements from a single point meteorological observation were used to initialize the shelterbelt model. The dispersion

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model produced spatial patterns of particle deposition that included the sharp near-source deposition gradient consistent with observations. The model tended to over-predict deposition away from the source field, which is the opposite of simulations with flow fields based on empirical relationships in the surface layer. Sensitivity tests reveal that the field-induced vertical velocity, which includes a strong updraft, promotes long-range dispersal. The enhanced turbulent kinetic energy above the maize field also promotes long-range dispersal. The altered turbulence and vertical velocity have smaller impacts than the reduction in wind speed over the field, which reduces pollen transport away from the field.

Keywords: Lagrangian, Pollen, Dispersion, Boundary Layer, Maize

3.2 Introduction

The open pollination of maize and the development of genetically modified varieties have lead to an increased need to accurately predict pollen transport, in order to assess the risk of outcross with non-GM varieties. Outcross increases potential for gene flow, with potential regulatory consequences (Jemison and Vayda 2001; Aylor et al. 2003; Garcia et al. 1998). Growers in the U.S. follow federal and state guidelines, with minimum distance requirements between fields based on size, barrier rows, and flowering dates (Baltazar and Schoper 2002; Ireland et al. 2006).

Local flow conditions affect the movement of maize pollen through the boundary layer. The large diameter (70 to 100 µm) and subsequent settling velocity (20 to 30 cm s\(^{-1}\)) of maize pollen result in much of the pollen being deposited inside the source field; as distance from the source increases, deposition decreases rapidly and then levels off (Raynor et al. 1972; Loubet et al. 2002; Jarosz et al. 2003). Reported deposition patterns are consistent with
pollination observations, in which 50% of individual plant kernels are the result of pollen released within a 12 m radius (Emberlin et al. 1999).

Despite the dominance of near-source pollination, low levels of maize out-crossing and maize pollen deposition have been observed at distances up to several hundred meters from the source of pollen (Ireland et al., 2006; Goggi et al. 2006). As demonstrated by Aylor et al. (2003), dispersion away from the field resembles as long tail consistent with a power-law relationship (see Bullock and Clarke 2000 for a discussion of the dispersive tail). In order to travel large distances, turbulent updrafts must overcome the terminal fall velocity and lift pollen to considerable heights (100s of meters) within the atmospheric boundary layer. Aircraft measurements of Brunet et al. (2003) indicate pollen through the entire depth of the boundary layer. Jarosz et al. (2003) explored components of the vertical flux of maize pollen and found that the flows encountered near changes in surface characteristic affect both convective and diffusive fluxes.

The complex flow near and within plant canopies must be accounted for in order to accurately predict pollen dispersal. Canopies significantly alter the mean and turbulent flow within and just above the canopy (Raupach and Thom 1981; Raupach et al. 1996; Finnigan 2000). Despite the complexities of canopy flow, several approaches generate a reasonable mean canopy wind profile (Raupach and Thom 1981; Cionco 1972). Extending above the canopy, a roughness sub-layer exists in which gradients are reduced and eddy diffusivities are enhanced (Cellier and Brunet 1992; Molder et al. 1999; Mahrt 2000).

With step changes in surface characteristics, such as surface roughness, internal boundary layers may develop over the downstream surface (Rao et al. 1974; Klipp and Mahrt 2003; Savelýev and Taylor 2001). As air passes over the new surface and the wind speed is
altered, the internal boundary layer (IBL) grows deeper until the surface layer is in equilibrium with the new surface properties. Within the IBL, there is a fully adjusted equilibrium layer extended from the ground and a layer above in which blending of the layers occurs (Garratt 1990). The IBL growth with distance follows a 4/5 power law, whether defined by velocity or Reynolds stress (Shir 1972). The IBL is largely governed by the larger roughness length scale (Wood 1982), with a long fetch required for a full equilibrium with the new surface (Taylor 1969). Based on field measurements (e.g. Bradley 1968; Munro and Oke 1975; Jegede and Foken 1999), empirical approaches in 2D (with a vertical component and a horizontal component aligned with the wind) have been used successfully to estimate the height of the IBL with distance from the step change (e.g. Savelyev and Taylor 2001, Panofsky and Dutton 1984, Wood 1982). These approaches don’t capture the complexity of the flow near the step change, since non-stationarity occurs near the layer of undulation (Klipp and Mahrt 2003). Several 2D numerical models based on mixing length or turbulence closure have been developed to simulate IBL development (e.g. Shir 1972; Rao et al. 1974; Taylor 1969).

Arritt et al. (2007) estimated the canopy influences on the flow field using scaling relationships. The canopy had a large impact on both the flow field and the subsequent dispersal of pollen. While the simulated deposition was similar to the observed deposition, the treatment of vertical velocity and turbulence was not realistic. This motivates our use of the Wang and Takle (WT) shelterbelt model, which simulates physically consistent flow fields and aids assessment of the effect of physical vegetative impacts on flow characteristics and subsequent pollen dispersal.
Numerous studies report observations of flow near natural and artificial windbreaks (e.g. Wilson, 2004), as well as wind tunnel simulations (e.g. Argent, 1992; Guan et al., 2003). Analytic solutions are problematic due to the complexity of the flow near windbreaks (Wang et al., 2001), but Reynolds-Averaged Navier Stokes (RANS) simulations (e.g. Wang and Takle, 1995a; Wilson, 1985) and large eddy simulation (Patton et al., 1998) have been successfully used to simulate the shelter effect.

The sheltering effect of windbreaks depends on height (H) and porosity, with the most extensive wind speed reduction for windbreaks with medium porosity (van Eimern 1964; Hagen and Skidmore 1971; Wang et al. 2001). The maximum wind speed reduction typically occurs ~5 H behind the barrier (Nord 1991; Bradley and Mulhearn 1983). Momentum budget analysis has revealed the importance of pressure perturbations, as well as advection terms and vertical turbulent transfer (Wang and Takle 1997a). The shelter effect is largely insensitive to shelterbelt width (Wang and Takle, 1996b) and shape (Wang and Takle 1997b), but is reduced for oblique flow (Seginer 1975; Wang and Takle 1996a; Wilson and Flesch 2003). The reduction of shelter effect is greatest for angles exceeding 30° from perpendicular to the shelter (Wang and Takle 1996a), with little protection downwind of corners due to enhanced downward momentum transfer in the lee (Richards 1984). The approach flow wind direction is altered by the shelter, first becoming more parallel and then shifting to more perpendicular as it moves through the shelter (Wang and Takle 1995b; Mulhearn and Bradley, 1977). Although non-neutral atmospheric stability reduces the shelter effect for non-oblique flow (Wilson, 2004a), the success of numerical simulations assuming neutral stability (e.g. Wang and Takle, 1995a) suggests that atmospheric stability effect is not a dominant factor during cases with high wind speeds.
In the case presented here, the maize canopy is much wider than a traditional shelterbelt. The maize canopy is nevertheless a wide barrier to the flow, somewhat analogous to a large array of closely spaced shelterbelts. The flow adjustment process is similar to internal boundary layer development, with the upwind breaks increasing larger-scale roughness (Judd et al. 1996). McAneney and Judd (1991) reported similarities between their fence arrays and plant canopies, with the largest flow adjustments from the initial upwind barriers (i.e. after the initial fences reduce the wind speed, further flow reduction is limited). Turbulence is enhanced downwind of multiple barriers, ultimately reducing the shelter effect of subsequent windbreaks (McAneney and Judd, 1991; Judd et al., 1996).

Several pollen and seed dispersal studies have employed Lagrangian random flight simulations for pollen dispersal (e.g. Di-Giovanni et al. 1995; Aylor et al. 2006; Jarosz et al. 2004; Arritt et al. 2007), as well as in dispersion applications of beads and spores (e.g. Wilson 2000; Aylor and Flesch 2001 Bouvet et al. 2006, 2007). The Lagrangian frame of reference moves with a virtual fluid particle, in contrast with the Eulerian frame of reference, which is fixed in space. With the Lagrangian particle method, the pollen cloud is represented as a large stochastic ensemble of virtual particles. Assessment of pollen viability may be aided by the estimation of temperature and humidity along with particle trajectory (for a discussion of viability, see Fonseca and Westgate 2005).

Lagrangian particle models have been implemented for maize pollen for two-dimensional flow fields (Jarosz et al. 2003, Aylor et al. 2006) and extended to three dimensions (Arritt et al. 2007). In the present study, we use the Wang Takle (WT) shelterbelt model to represent the complex flow near the maize field and explore the sensitivity of the results to the field-altered vertical velocity and turbulence. We compare the results with the
simulations of Arritt et al. (2007), in which scaling relationships were used to generate the flow fields.

3.3 Materials and methods

3.3.1 Lagrangian dispersion model

Here we summarize the Lagrangian particle dispersion model (LPD), with details provided in Arritt et al. (2007). This approach is attractive for pollen dispersal, since it allows the tracking of individual particles and can be applied to complex flow fields. Particle motion follows the mean wind and a turbulent stochastic wind component. The turbulent component follows a random flight, consistent with an auto-regressive model and Markov chain process (Smith 1968; Hall 1975). Several Lagrangian particle models have been developed in recent decades, based on varying flow assumptions (see Sawford 1985, Wilson and Sawford 1996). Following the development of corrections for unrealistic drift (Legg and Raupach 1982), the well-mixed condition as proposed by Thompson (1987) has become the standard for the selection of model parameters (Wilson and Sawford 1996).

The three-dimensional model used here includes the Legg and Raupach (1982) drift correction term and gravitational settling in the vertical dimension. The model is flexible in terms of its source of meteorological input for wind and turbulence fields. The meteorological data may be taken from atmospheric model results, or profiles generated from field observations (as in Arritt et al., 2007). The simulations reported here used flow fields from the Wang and Takle (WT) shelterbelt model, which was initialized using near-surface weather data from a single station near the maize field.
3.3.2 Wang and Takle shelterbelt model

For the present study, the flow fields were provided by the Wang and Takle (WT) shelterbelt model, which has been converted to 3D. WT has previously been adapted for oblique flow, in which 3D wind components are simulated in 2D space (one horizontal coordinate perpendicular to the shelter and one vertical coordinate). To our knowledge, this is the first full 3D implementation of a shelterbelt model. The WT model assumes neutral stratification and is non-hydrostatic and incompressible, with equations developed using phase averaging followed by Reynolds averaging (Wang and Takle, 1995a,b, 1996a,b, 1997a,b). The phase averaging is applied to the equations of motion and continuity equation over a scale smaller than scale of mean variation, but larger than the shelter elements; the procedure results in additional terms in the momentum and turbulent kinetic energy equation.

The 3D equations for the horizontal \((u,v)\) and vertical \((w)\) motion and continuity relation are:

\[
\begin{align*}
\frac{\partial u}{\partial t} = & -\frac{1}{\rho_0} \frac{\partial p}{\partial x} - u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} - w \frac{\partial u}{\partial z} - \frac{\partial u^2}{\partial x} - \frac{\partial u v}{\partial y} - \frac{\partial u w}{\partial z} - C_D A U u \\
\frac{\partial v}{\partial t} = & -\frac{1}{\rho_0} \frac{\partial p}{\partial y} - u \frac{\partial v}{\partial x} - v \frac{\partial v}{\partial y} - w \frac{\partial v}{\partial z} - \frac{\partial u v}{\partial x} - \frac{\partial v^2}{\partial y} - \frac{\partial v w}{\partial z} - C_D A U v \\
\frac{\partial w}{\partial t} = & -\frac{1}{\rho_0} \frac{\partial p}{\partial z} - u \frac{\partial w}{\partial x} - v \frac{\partial w}{\partial y} - w \frac{\partial w}{\partial z} - \frac{\partial u w}{\partial x} - \frac{\partial v w}{\partial y} - \frac{\partial w^2}{\partial z} - C_D A U w \\
\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) = & 0
\end{align*}
\]

The variables without primes are resolved grid-scale variables, while primes indicate parameterized turbulent components; \(u'\), \(v'\) and \(w'\) are horizontal and vertical turbulent components of the wind, \(U\) is the total wind speed in 3D space, \(C_D\) is the leaf drag
coefficient, $A$ is the leaf area density ($m^2 m^{-3}$), $p$ is the pressure perturbation, and $\rho$ is air density. Due to the small scale of shelterbelts, the Coriolis deflection is neglected. The terms on the right hand side of equations 2-4 represent pressure gradient force, advection (3 terms), turbulent diffusion (3 terms), and drag force per unit volume. Turbulence closure for the diffusion terms uses second-order scheme following Yamada (1982) with a prognostic equation for turbulent kinetic energy. The model generates steady state fields of mean and turbulent flow components. The turbulent diffusion terms are parameterized following Mellor and Yamada (1982).

The turbulent kinetic energy (TKE) is determined from the following prognostic equation, in which $\Lambda$ is a length multiplied by 16.6:

$$\frac{\partial E}{\partial t} = -u_i \frac{\partial E}{\partial x_i} - u_j u_i \frac{\partial u_j}{\partial x_i} + \frac{\partial}{\partial x_i} \left( K_E \frac{\partial E}{\partial x_i} \right) + C_D A U^3 - \frac{(2E)^{2/3}}{\Lambda}; \text{ i,j =1,2,3} \quad (5)$$

The first term on the right hand side represents advection of TKE. In the present study, horizontal and vertical advection terms are important due to the sharp gradient of TKE near the top of the maize canopy. The second term on the right hand side represents shear production of TKE, which peaks in high-shear regions near the ground and the top of the maize canopy. Turbulent transport (term 3 on the right hand side) diffuses TKE away from regions of maximum production, spreading out the zone of elevated TKE; although horizontal diffusion terms are included, the vertical diffusion term is far more important. The shelter-induced mechanical term (term 4 on the right hand side) produces TKE as the drag force of the shelter reduces the mean wind speed and converts mean kinetic energy to TKE.
The turbulent fluxes required for the prognostic momentum and TKE equations are parameterized using eddy viscosity \( (K) \); for example, the kinematic turbulent vertical flux of the horizontal \( u \) component becomes:

\[
-u_iu_j' = K_m \left( \frac{\partial u_i}{\partial x_j} \right), \quad i, j = 1, 2, 3
\]

(6)

The turbulent transfer coefficients for momentum \( (K_m) \) and TKE \( (K_E) \) required for the turbulence closure are determined from turbulent kinetic energy, \( E \), the empirical constant \( c \) (=0.74), and length scale \( l \).

\[
K_m = K_E = cl\sqrt{E}
\]

(7)

The model is initialized with the surface layer wind profile, calculated using single point wind data. Within the surface layer, which typically constitutes the lowest ~10% of the boundary layer, the mean wind speed follows the logarithmic wind profile (Stull 1988; Garratt 1992):

\[
u(z) = \phi_m \left( \frac{u_*}{k} \right) \ln \left( \frac{z}{z_0} \right)
\]

(8)

The shelter configuration is provided via the leaf area density \( (A) \), which relates to the pressure loss coefficient \( (k_r) \) through the following (Wang and Takle, 1995b; Wilson, 1985):

\[
k_r = C_D \int A \, dx
\]

(9)

Due in part to the large width of the maize field, the simulated flow fields are not sensitive to changes in leaf area density or leaf drag coefficient. For the simulations here, the canopy leaf
area density was 1.5 m² m⁻³ and the leaf drag coefficient was set to 0.1. Numerous tests revealed little sensitivity to the values of the leaf area density and drag coefficient.

The prognostic equations of motion and TKE are discretized on a finite difference grid. A modified Crank-Nicholson scheme is used for the numerical solution of diffusion terms, with successive over-relaxation (SOR) subsequently applied to the dynamic pressure field. The pressure gradient terms are omitted from the equations of motion each time step, with first guess auxiliary wind components generated first. The pressure gradient-generated flow accelerations are subsequently applied after SOR determines the pressure field. The pressure relates to the divergence of the wind components through the following:

$$
\left( \frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} \right) \rho = \frac{1}{\Delta t} \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right)
$$

The model is simulated until it converges to a steady-state solution based on a minimal one time step change in grid-averaged mean kinetic energy.

### 3.4 Results

Predicted pollen deposition was compared with observations from a field experiment near Ames, Iowa for the period of 8, 9, 10 and 11 August 2003 (Arritt et al. 2007). The dispersion results using the shelterbelt model are also compared with dispersion model results using scaling relationships for the flow field (from Arritt et al. 2007). The source field was ~90 m x 90 m of a commercial maize hybrid planted at approximately 7 plants m⁻² and was surrounded by a field of soybeans. The maize canopy was ~2.2 m high and the soybean canopy was ~1 m high. Pollen was collected daily on 12 equally spaced receptors inside the source field, along with 136 traps located approximately 1, 10, 135, 100, 150, 200, and 250
m from the source field in the N, NW, E, SE, S, SW, W, and NW directions (see Arritt et al. 2007).

Flow fields were generated on a discrete three-dimensional grid. Horizontal grid spacing of the 600 by 600 m model domain was 2 m in both the $x$ and $y$ dimensions in the center of domain, with 10 m spacing for the 100 m on each edge. The vertical spacing was 0.5 m up to 7 m and increased by a factor of 1.15 for each level up to the domain top at 85 m. The time step was $\Delta t = 0.5$ s for the dispersion simulations and 0.075 s for the steady state shelterbelt simulations. Wind data were observed by portable weather stations located near the north and south edges of the field. The dispersion model was simulated for each hour during the day using the wind observation that was upwind from the maize field. The dispersion model continually released virtual pollen grains at a height of 2.2 m during the course of each simulation, with a total of 8,644,000 virtual pollen grains released in each hourly simulation. A uniform area source was approximated by using 2161 source locations spaced evenly throughout the maize field, corresponding to each point of the 2x2 m horizontal grid.

Results for each day were compiled by combining the hourly simulations, with the individual hourly simulations weighted using an idealized pattern of diurnal pollen shed peaking in late morning (Westgate, unpublished). Although the number of simulated pollen grains is still much smaller than actual pollen shed, we released 20 times the amount of pollen released in our earlier study (Arritt et al. 2007). This much larger sample provided more reliable statistics far from the field (where model deposition is small) and allowed us to explore variability among subsets of the large sample. To simplify comparisons between predicted and observed values, both were scaled to a maximum of 100. The results were also
compared with the Arritt et al. (2007) simulations, which used surface layer profile scaling relationships for flow fields.

Spatial patterns of accumulated daily observed (Figure 3.1) and simulated (Figure 3.2) deposition are generally similar, with deposition maxima over the field and greater far-field deposition downwind of the field (wind roses provided in Arritt et al. 2007). However, simulated deposition patterns illustrate greater deposition well away from the field, especially southwest of the field on 08 and 10 August. As noted in Arritt et al. (2007), the simulated patterns tend to be more uniform and smoother than the observed deposition. This is likely due in part to the model assumption of uniform pollen release within the field, and the sub-day dependence of shed on wind characteristics. Nonetheless, alternative scaling to field mean (instead of field maximum) does not dramatically change the results. The actual pollen shed near the field edge may be more important. Reduced pollen shed near field edges would explain some of the model error near the field, but there is no reason to suspect such a shed reduction during this field experiment.

Downwind transects for each day (Figure 3.3) illustrate that the model captured the sharp gradient of deposition near the source, but deposition at greater distances tended to be over-predicted when using the shelterbelt model. The over-prediction is small, but systematic. It is worth noting that log scaling highlights the error far the field, while linear scaling (not shown) makes visual distinction of observations and model results difficult except near the field. The model error using the shelterbelt model is quite different than the error using scaling relationships for the flow field (as discussed in Arritt et al. 2007), in which there is an under-prediction of deposition at large distances from the field (see the original scaling results on Figure 3.3).
The number of particles pollen shed with the WT simulations is 20 times as large as the original scaling flow field simulations in Arritt et al. (2007). New simulations using the scaling flow fields, but with greater pollen release equivalent to the WT-driven simulations, continue to illustrate reduced long-range deposition relative to the WT results (Figure 3.3). However, the difference is smaller as deposition far from the field increases. As noted in Arritt et al. (2007), the comparatively limited pollen release in that study reduced the likelihood of any simulated pollen far from the field. This suggests that some of difference between observed and simulated deposition is explained by sampling. The observed downwind pollen far from the field (>150 m) is quite small, with zero or a few pollen grains observed in each trap. Given small amounts of actual and simulated pollen deposition far from the field, it may be that the simulated model pollen is more likely to be counted than the real-world pollen.

Exploration of all observed locations reveals several locations with high model deposition, but modest observed deposition (Figure 3.4). This is due in part to the simulated within-field variability being much less than the observed variability. For example, the observed within-field range is 60% of the field maximum, but the simulated range is 20%. Some of this within-field error may be due to variability of within-field shed. In addition to within-field and the smaller far-field error, the model also over-predicts near field deposition in some cases. Scaling to field mean reduces some of the near-field error, but it is still present. There are a few locations with greater observed than predicted deposition, but this is the exception.

Breaking our simulated sample into 20 sub-samples allows an examination of the sampling error associated with using a small number of simulated particles. Each sub-sample
contains the same amount of pollen released as the simulations in Arritt et al. (2007); for
direct comparison, we also broke up the new simulations using the scaling flow fields into
sub-samples. In addition to aiding model validation, the sub sampling could be useful in
assessment of outcross potential. In an absolute sense, sub-sample to sub-sample variability
is maximized close to the field and decreases with distance (Figure 3.5). In a relative sense,
the far-field locations have much greater variability. The sub samples allows assessment of
whether the observed value is within model sub sample variability; in the 10 August
example, the simulated pollen is greater than observed for nearly every sub sample at the
three shown locations. The sub-sample variability using the scaling flow fields is similar to
that for the shelterbelt-driven simulations near the field. At greater distances from the field,
most of the scaling flow field simulated values are zero. The sub simulation variability is
damped far from the field because little model pollen is transported there.

3.5 Analysis of the flow field

3.5.1 Observed and simulated wind near the field

The spatially-limited wind observations within and near the field make assessment of
the model predicted flow fields difficult. The wind observations placed immediately inside
the field at the north and south edges show a systematic reduction of wind speed on the
downwind side, since the north station was upwind on all days but 10 August (Figure 3.6).
The reduction in downwind wind speed is greater for higher upstream wind speed, with a
peak difference of ~1 m s\(^{-1}\) over the period (Figure 3.7). It should be noted that this is an
under-estimation of the actual field effect, since the upstream observation is also slowed
somewhat by the field. The model-predicted wind speed at the field edges (Figure 3.8) shows
qualitatively similar behavior; however, there is a greater reduction in wind speed at the downwind edge (up to 1.5 m\textsuperscript{s}\textsuperscript{-1}).

To illustrate the effect of the maize canopy on the flow in a simplified case, we present flow fields for cases with 0.5 and 2 m\textsuperscript{s}\textsuperscript{-1} westerly flow (roughly coinciding with the observed range in wind speed in the present study). With weak upstream flow (approaching free convection, but included for comparison), there is a reduction of wind speed over the field, but little indication of internal boundary layer development (Figure 3.9). There is also a modest turbulent kinetic energy (TKE) increase at and above the top of the maize canopy (Figure 3.10). The convergence at the leading edge results in a weak updraft, coupled with subsidence at the downwind edge of the field (Figure 3.11). With stronger upstream flow, there is a larger fractional reduction of wind speed over the field, with growth of an internal boundary layer with distance from the field edge. As with lighter upstream flow, TKE is enhanced at the leading edge of the field. There is also increased TKE in the enhanced wind shear zone sloping upward over the field; the associated peak is near the downwind field edge roughly 5 m above the canopy. The peak TKE increases as the upstream wind speed increases, since the shear production and shelter-induced mechanical generation are enhanced. The downwind displacement of the peak upward vertical motion occurs due to the downwind shift in the location of strongest wind convergence.

With upstream flow into the corners, the WT flow field is qualitatively similar. With 2 m s\textsuperscript{-1} upstream flow from the southwest, there is substantial wind reduction over and within the field and a region of slightly accelerated flow downwind of the field (Figure 3.12). Oblique flow with typical windbreaks limits the shelter effect in the lee, but in this case the
wide extent of the canopy produced similar flow reduction within and very near the field as the non-oblique flow.

The WT flow fields are more complex and physically consistent than the scaling flow used in Arritt et al. (2007). The scaling horizontal wind flow (Figure 3.13) for 2 ms$^{-1}$ westerly flow is similar to the WT simulation, but the minimum wind speed is greater. The scaling flow fields also cannot generate the TKE maximum near the top of the canopy or realistic vertical motion. The difference in deposition using WT and scaling flow fields is due to the combined effect of the altered wind speed, TKE, and vertical velocity. The modestly greater wind speed reduction at and above the canopy produced by the WT flow fields generates somewhat greater (~3%) within-field pollen deposition than the scaling flow simulations, with a corresponding reduction in deposition downwind near the field. At greater distances from the field, the WT simulation pollen deposition is greater. This is due in part to the faster WT wind recovery in the lee of the maize field, along with the effect of the WT vertical velocity and augmented near-canopy top TKE.

3.5.2 Sensitivity to vertical velocity and turbulent kinetic energy

Arritt et al. (2007) discussed the role of the maize field-induced wind speed reduction, wherein the horizontal wind speed reduction over the field inhibits pollen dispersal away from the field. Arritt et al. (2007) also discussed the role of vertical velocity and the limitations of the scaling-generated flow fields. Here we explore the impacts of the vegetative cover contrast-induced vertical velocity and TKE, which also affected pollen dispersal. For the vertical velocity sensitivity, vertical velocity was set to zero while mean horizontal wind components and TKE remained the same as in the validation simulations.
For the TKE sensitivity, TKE was set to the unperturbed upstream value while horizontal and vertical wind mean components were unaltered. With vertical velocity set to zero (Figure 3.14), there is greater pollen deposition within the field and less deposition for modest distances from the field (with very small differences at large distances from the field). This result is unsurprising given the updraft over portions of the field, and consistent with the findings using a simpler treatment for vertical velocity (Arritt et al. 2007). The upstream TKE simulation also produced a reduction in deposition at moderate distances from the field, as well as a small increase within the field (Figure 3.14). Physically, the enhanced turbulence increases the likelihood of turbulent vertical velocities lifting the pollen to altitudes where the horizontal wind speed is higher. The vertical velocity and TKE effects on pollen dispersal are smaller than the effect of the reduced wind speed on dispersal, but they offset some of the total maize field impact by promoting dispersal away from the field.

### 3.6 Conclusions

A three dimensional Lagrangian model of maize pollen dispersion has been coupled with a newly-developed 3D implementation of the Wang Takle (WT) shelterbelt model and tested using field data collected in central Iowa during August 2003. Using single point wind observations to initialize the shelterbelt model, the model captured the sharp deposition gradient near the source field. The model produces a dispersive tail of low deposition at greater distances from the field, yet simulations tended to deposit too much pollen downwind of the field.
The model over-prediction of deposition at large downwind distances is likely due to a combination of deficiencies in model formulation (both WT and LPD) and sampling differences between the model results and observations. The inability to include within-field variations in pollen shed results in model deposition that is much less variable within the field; however, scaling to field mean (not shown) does not have a large effect on the results. The limited wind observations make full assessment of the flow fields difficult. The observations suggest that the model reduction in downwind flow near the field is too great during windy conditions. The direct effect of this error, however, should produce less deposition downwind of the field (the opposite to the observed error). On the other hand, too large a wind speed decrease leads to greater convergence and upward motion (consistent with the observed deposition error). While the TKE and vertical velocity fields have a meaningful impact, the sensitivity tests (w=0 and upstream unperturbed TKE) suggest that they cannot explain the far-field error.

Along with potential deficiencies in the dispersion model and flow fields, some far-field error is likely due to a difference in sampling. The low amounts of observed pollen far downwind of the field may be due in part to sampling problems. Some of the downwind traps far from the field collected no pollen, while others collected just a few pollen grains. The low concentration of pollen far from the field increases the probability that a small pollen trap will not collect any pollen. The much larger deposition region in the model increases the chance that pollen will be counted far from the field.

Using a larger number of simulated particles results in a smoother deposition reduction with distance from the field. Breaking the large sample into sub-samples allows an assessment of simulated deposition variability at specific locations. The sample-to-sample
variability is maximized within and near the field, while the relative variability is greater at large downwind distances. These sub-samples illustrated that the aforementioned model bias, while small in some cases, is systematic among most sub-samples downwind of the field. This within-case variability could also be used in the formulation of outcross risk assessment, by providing an error estimate in simulated pollen deposition.

The maize field impacts the pollen flow by a reduction in horizontal wind speed, an updraft with location sensitive to upstream velocity, augmented TKE at and above the field, and the development of an internal boundary layer. Sensitivity tests revealed that the field-induced vertical velocity decreases within-field deposition and increases deposition out to moderate distances from the field. The increase in TKE above the canopy also promotes dispersion away from the field. The relative impacts of horizontal flow, vertical velocity, and TKE may be sensitive to field configuration.

3.7 Acknowledgements

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3.8 References


3.9 Figures

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Figure 3.2. Logarithm (base 10) of simulated pollen deposition on 8, 9, 10, and 11 August 2003.
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Figure 3.14. Transect in the downwind direction of the logarithm (base 10) of observed pollen deposition and of simulated deposition with the sensitivity to turbulent kinetic energy (TKE) and vertical velocity (w).
CHAPTER 4. THE OBSERVED AND SIMULATED EFFECT OF A FIELD-EDGE BORDER ON MAIZE POLLEN DISPERsal

A Paper to be submitted to Field Crops Research

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4.1 Abstract

A field experiment in Iowa explored the effect of a sorghum border on the dispersal of maize pollen. We hypothesize that field edge borders reduce pollen transport away from the field by reducing the low-level wind speed. Two 100 by 100 m maize plots were planted in the middle of a large soybean field; one of the maize plots had a border of ~2.7 m tall sorghum and the other field, taken as the control, did not have a border. We used Lagrangian particle dispersion (LPD) simulations to explore the sensitivity of pollen dispersal to the border and compared the results with observed maize deposition. The Wang Takle (WT) shelterbelt model has been extended to three dimensions and used to provide flow fields for the LPD simulations. The WT flow fields reveal that the border affects the flow within and near the field, while the maize field itself acts as an effective shelter. Both control and border fields have a reduction of wind speed within and above the canopy, with an increase in

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turbulence kinetic energy and a region of induced upward vertical motion above the maize canopy.

The border field was observed to have modestly less long-range (>100 m) dispersal than the control field, with more mid-range dispersal (~30 to 50 m). The model produced realistic spatial patterns of particle deposition for both fields that included the sharp near-source deposition gradient and longer-range dispersive tail. In general, the model deposited too little pollen at mid distances from the field and too much deposition at larger distances.

The model-produced deposition spatial patterns for the border and control field are similar. The chief differences are a modest increase in within-field deposition and a slightly faster downwind decrease in deposition with distance for the border field. This results in decreased downwind pollen deposition for the border field. The effect of the border on long-range dispersal is small in absolute terms, but large in relative terms (~up to 50% simulated deposition reduction in some locations). Borders may reduce the probability of outcross between neighboring fields, but caution is advised before generalizing these results to very large distances from the field (outside the horizontal scale of the present study) or markedly different field configurations. While both the border and maize field affect the flow and subsequent dispersal, the model is not highly sensitive to border width and height. Since the simulated results are qualitatively similar to the observations, the model may be a useful tool for diagnosing the potential effect of field borders on dispersal in varying environmental conditions.

Keywords: Lagrangian, Pollen, Dispersion, Boundary Layer, Maize
4.2 Introduction

The need for accurate simulation of maize pollen dispersal has been driven by the desire to control outcross between genetically modified maize with conventional or organic varieties (e.g. Aylor et al. 2003, 2006; Jarosz et al. 2003). While biological factors and field design strongly influence sources of pollen, viability, and outcross risk (Westgate et al. 2003; Fonseca and Westgate 2005), atmospheric flow determines pollen dispersal and the subsequent likelihood of adventitious pollen being present. Higher wind speeds promote dispersal to greater distances from the source; turbulence also promotes dispersal, as turbulent eddies lift pollen well into the boundary layer (Aylor at al. 2006). Aircraft measurements indicate maize pollen mixed throughout the daytime boundary layer (Brunet et al. 2003), which allows transport to greater distances from the field.

Due to its large settling velocity (20 to 30 cm s\(^{-1}\)), a large fraction of the maize pollen shed is deposited within the source field (Raynor et al. 1972; Jarosz et al. 2003). Deposition is greatest within 1-3 m of the field (Loubet et al. 2002), decreases sharply with increasing distance from the field, and then levels off with a long tail (Bullock and Clarke 2000; Aylor et al. 2003). Out-cross observations are consistent with these findings, with most kernels resulting from nearby pollen (Emberlin et al. 1999). However, low levels of maize out-cross have been observed at distances from the field of 200 meters and beyond (Ireland et al., 2006; Goggi et al. 2006).

In the case studied here, a taller sorghum border was planted around the edge of the maize field. The sorghum border on each side of the field acted as a shelterbelt. Shelterbelts, which are simply natural structures that act as windbreaks, have been extensively studied with observations (e.g. Wilson 2004), wind tunnel simulations (e.g. Argent 1992), and
numerical modeling (e.g. Wang and Takle 1995a, Wilson 1985; Patton et al. 1998) have been successfully used to simulate the shelter effect.

The primary characteristics of a windbreak are its height (H) and porosity. The most extensive wind speed reductions are for windbreaks with medium porosity (von Eimern, 1964; Hagen and Skidmore, 1971; Wang et al., 2001). The wind minimum is generally less than 40% of the upstream wind speed and occurs is roughly 5H or less behind the barrier (e.g. Nord 1991.; Bradley and Mulhearn, 1983). For a typical windbreak, the wind speed slowly recovers downwind of the minimum, reaching 80% of the upstream value at 20H (Raine and Stevenson, 1977). Some small effect of drag on the wind speed may still be felt at 30H or beyond (Jacobs, 1984; Bradley and Mulhearn, 1983).

For a given shelterbelt density, the shelter effect is largely insensitive to the width of the shelterbelt (Wang and Takle, 1996). For less dense windbreaks, the position of minimum wind speed shifts downstream, while higher density windbreaks have greater protection near the shelter and faster recovery (Hagen and Skidmore, 1971). The importance of vertical porosity distribution has been long debated, with conflicting observations (Heisler and Dewalle, 1988). Greater density in the upper portion of the shelter increases drag where the approach flow is stronger, but also increases the likelihood of reverse flow in the near-lee.

Wang and Takle (1997b) discuss the importance of pressure perturbations on flow behavior in the lee of the shelter; the perturbations are positive immediately upstream of shelter and negative in the lee, followed by a downstream plateau. The resulting pressure gradient in the lee opposes the flow and enhances the direct shelter effect of the drag force. Their analysis of the momentum budget reveals the importance of horizontal and vertical advection terms, which are significant due to large velocity gradients near the shelter. The
vertical turbulent transfer is important (though not dominant), particularly near the top of the shelter where turbulent kinetic energy (TKE) generation is greatest. The horizontal turbulent transfer is very small. Patton et al. (1998) present similar findings, with vertical turbulent transport balancing horizontal advection.

With oblique flow, in which the wind direction is not perpendicular to the shelter, the reduction in wind is weaker and does not extend as far downwind from the shelter (Seginer, 1975; Wang and Takle, 1996; Wilson and Flesch, 2003). The reduction of shelter effect is greatest for angles exceeding 30° (Wang and Takle, 1996). With a higher incidence angle, the increased drag force leads to wind speed reduction, while the increased parallel component of the wind reduces the shelter effect. As discussed in Wang and Takle (1996), the enhanced drag effect is more important for low-density shelters, while the reduced perpendicular flow is more important for dense shelters. The net reduction of sheltering is particularly acute in the case of upstream flow into the corners of rectangular plots, with little protection downwind of corners due to enhanced downward momentum transfer in the lee (Richards, 1984).

The shelter also influences the approach flow wind direction, which initially becomes more parallel and then shifts to more perpendicular as it moves through the barrier (Wang and Takle, 1995b; Mulhearn and Bradley, 1977). Interestingly, the effect of shelterbelts on mean and turbulent flow is largely insensitive to the shape of the barrier, despite changes in drag force and pressure (Wang and Takle, 1997b). The pressure loss (or resistance) coefficient, often used as an indication of shelter effectiveness, is greater for rectangular or triangle shaped shelterbelts. There is greater flow deceleration close to the barrier, but greater acceleration in the near lee. Wang and Takle (1997b) conclude that the presence of both
positive and negative pressure gradients in the lee of the shelter reduces the shape sensitivity. This suggests some limitation of the pressure loss coefficient as an indication of shelter efficiency, although Wilson (2004) argues that the resistance coefficient determines potential shelter effect.

In addition to the effect of the shelterbelt, the flow is also substantially altered by the presence of canopy (Raupach and Thom 1981; Raupach et al. 1996; Finnigan 2000). In many cases, maize fields are adjacent to a region with a different surface characteristic. Step changes in surface characteristics result in internal boundary layers that develop over the downstream surface (Rao et al. 1974; Klipp and Mahrt 2003; Savelyev and Taylor 2001). In the cases evaluated by Arritt et al. (2007) and Clark et al. (2007), in which a maize field was surrounded by soybean, the change in surface characteristic altered the flow and pollen dispersal. In the cases studied here, the effects of both the field-edge border and soybean to maize transition are important.

4.3 Materials and methods

4.3.1 Lagrangian dispersion model

Arritt et al. (2007) provide the details of the Lagrangian particle model (LPD), while we briefly summarize the approach here. Lagrangian simulations of maize pollen have been used in several reported studies for both two dimensional (Di-Giovanni et al. 1995; Aylor et al. 2006; Jarosz et al. 2004) and three dimensional flow fields (Arritt et al. 2007, Clark et al. 2007). The Lagrangian frame of reference moves with a virtual particle, allowing particle tracking. With this approach, particle motion follows both the mean resolved flow and
turbulent velocities generated by a stochastic approach consistent with auto-regressive processes (Smith 1968; Hall 1975). Lagrangian particle models make at least implicit use of the Langevin equation, with several models having varying flow assumptions developed in recent decades (Legg and Raupach 1982, Sawford 1985). Following the development of drift corrections (Legg and Raupach 1982), the well-mixed condition proposed by Thompson (1987) has become the standard criterion for model development (Wilson and Sawford 1996). The LPD used here includes the Legg and Raupach (1982) drift correction term and the superimposition of the terminal fall speed to account for gravitational settling (following Aylor et al. 2003). The dispersion simulations reported here were initialized using flow fields from the Wang and Takle (WT) shelterbelt model (as in Clark et al. 2007).

4.3.2 Wang and Takle shelterbelt model

In the present study, both the border and maize canopy act as barriers to the flow. The border is similar to a typical shelterbelt, while the maize canopy is shorter and much wider. The flow adjustment process over the maize is similar to internal boundary layer development, with the upwind and downwind sorghum providing additional shelter.

The flow fields were provided by the 3D version of the Wang and Takle (WT) shelterbelt model. Here we provide a brief summary of the model, with the 3D implementation discussed in Clark et al. (2007) and original model formulation discussed in Wang and Takle (1995a,b; 1996). The model is non-hydrostatic and incompressible, with neutral stability and Boussinesq assumptions. In the original model development, phase averaging was applied over a scale smaller than the scale of mean variation, but larger than the shelter elements. This resulted in additional terms related to drag in the momentum and
The turbulent kinetic energy equation. The 3D equations for the horizontal \((u, v)\) and vertical \(w\) motion and continuity relation are:

\[
\frac{\partial u}{\partial t} = -\frac{1}{\rho_0} \frac{\partial p}{\partial x} - u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} - w \frac{\partial u}{\partial z} - \frac{\partial u^2}{\partial y} - \frac{\partial u v}{\partial z} - \frac{\partial u w}{\partial z} - C_D A U u
\]  

\[
\frac{\partial v}{\partial t} = -\frac{1}{\rho_0} \frac{\partial p}{\partial y} - u \frac{\partial v}{\partial x} - v \frac{\partial v}{\partial y} - w \frac{\partial v}{\partial z} - \frac{\partial u v}{\partial x} - \frac{\partial v^2}{\partial y} - \frac{\partial v w}{\partial z} - C_D A U v
\]  

\[
\frac{\partial w}{\partial t} = -\frac{1}{\rho_0} \frac{\partial p}{\partial z} - u \frac{\partial w}{\partial x} - v \frac{\partial w}{\partial y} - w \frac{\partial w}{\partial z} - \frac{\partial u w}{\partial x} - \frac{\partial v w}{\partial y} - \frac{\partial w^2}{\partial z} - C_D A U w
\]  

\[
\left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) = 0
\]

The variables without primes are resolved grid-scale variables, while primes indicate parameterized turbulent components; \(u', v'\) and \(w'\) are horizontal and vertical turbulent components of the wind, \(U\) is the total wind speed, \(C_D\) is the leaf drag coefficient, \(A\) is the leaf area density \((m^2 m^{-3})\), \(p\) is the pressure perturbation, and \(\rho\) is air density. Due to the small scale of shelterbelt, Coriolis deflection is neglected. The terms on the right hand side represent pressure gradient force, horizontal and vertical advection (3 terms), turbulent diffusion (3 terms), and drag force per unit volume. The turbulent diffusion terms are parameterized with simplified closure based on Mellor and Yamada (1982), in which eddy diffusivity is determined by a prognostic equation for turbulent kinetic energy. Wang and Takle (1995b) and Wilson (1985) both found that shelterbelt results were insensitive to choice of closure scheme.

The turbulent kinetic energy (TKE) is determined from the following prognostic equation, in which \(\Lambda\) is a length scale multiplied 16.6:
\[
\frac{\partial E}{\partial t} = -u \frac{\partial E}{\partial x} - v \frac{\partial E}{\partial y} - w \frac{\partial E}{\partial z} - u_j \frac{\partial u_i}{\partial x_j} + \frac{\partial}{\partial x_i} \left( K_E \frac{\partial E}{\partial x_i} \right) + C_D A U^3 - \frac{(2E)^{2/3}}{\Lambda}; \ i,j=1,2,3
\] (5)

The first three terms on the right hand side represent advection of TKE by the mean wind, followed by shear production, turbulent transport, shelter-induced mechanical production, and dissipation. In the present study, horizontal and vertical advection terms are important due to the sharp gradient of TKE near the shelter and maize canopy. The shear production term reflects the mechanical generation of TKE in high-shear regions, such as near the ground and near the top of the maize canopy and border. The turbulent transport terms diffuse TKE away from regions of maximum production; although horizontal diffusion terms are included, the vertical diffusion term is more important. The shelter-induced mechanical term produces TKE as the drag force reduces the mean wind speed and converts mean kinetic energy to TKE.

The prognostic equations are discretized on a finite difference grid. A modified Crank-Nicholson scheme is used for the numerical solution of diffusion terms, with successive over-relaxation (SOR) subsequently applied to the dynamic pressure field. The pressure gradient terms are omitted from the equations of motion, with pressure gradient-generated flow accelerations applied after SOR determines the pressure field. The model runs until it converges to a steady-state solution based on changes in grid-averaged mean kinetic energy.

The model is initialized with the logarithmic surface layer wind profile, generated from single point wind data and estimated displacement height and roughness length. Due in part to the substantial width of the shelter, the simulated flow fields are not sensitive to changes in leaf area density or leaf drag coefficient. For the simulations here, the canopy leaf
area density was $1.5 \text{ m}^2\text{m}^{-3}$ and the leaf drag coefficient was set to 0.1 (Hurtalova et al 2002). For simplicity, and since the sorghum density was similar to the maize, the same values were used for the sorghum border. Numerous tests revealed little sensitivity to the values of the leaf area density, drag coefficient, or border width.

4.3.3 Field data and numerical simulations

Predicted pollen deposition was compared with field experiment observations near Rockwell City, Iowa on 9, 10, and 14 August 2005. The field experiment is described in detail in Astini (2007) and summarized here. At each site, ~100 m by 100 m maize fields of ~1.7 m dwarf variety were planted with a density of $\sim 6.8 \times 10^4 \text{ ha}^{-1}$ in the center of large soybean field with average plant height of ~0.8 m. An additional ~6 m wide sorghum border was placed around one of the fields. During the collection period, the border was ~1 m taller than the maize. Pollen was collected daily on 9 equally spaced receptors inside each source field, along with 139 traps located approximately 1, 3, 5, 15, 25, 40, 60, 90, 120, 160, 220, and 300 m from the source field along the cardinal directions (Figure 4.1).

Flow fields were generated using the shelterbelt model on a discrete three-dimensional grid. Horizontal grid spacing of the 700 by 700 m model domain was 2 m in both the $x$ and $y$ dimensions over most of the domain, with 15 m spacing for the 150 m on each side (this region is far enough from the maize and border that little change occurs there). The vertical spacing was 0.5 m up to a height of 7 m and then increased by a factor of 1.15 for each level up to the domain top at 85 m. The time step was $\Delta t = 0.5 \text{ s}$ for the dispersion simulations and 0.075 s for the steady state shelterbelt simulations. Wind data were collected by a portable weather station placed at a location in the undisturbed flow and also by a
station within each maize field; hourly upwind data was used to initialize the shelterbelt simulations. Wind roses for 9, 10, and 14 August 2005 are provided in Figure 4.2.

The WT flow fields were used to drive the dispersion simulations, with 10 hourly simulations. For each hourly dispersion simulation, 9,996,000 virtual pollen grains were released for each field. A uniform area source was approximated by using 2499 source locations spaced evenly throughout the maize field, corresponding to each point of the 2 x 2 m horizontal grid. Results were compiled by weighting the hourly simulations using an idealized pattern of diurnal pollen shed (Westgate, unpublished). Rather than counting simulated deposition on a grid, model pollen was counted over a 2 by 2 meter region centered at each observed location. For comparison of predicted and observed values, both were scaled to a maximum of 100.

4.4 Results

Scaling issues complicate the comparison of the observed fields, since two of the three days shown (the later days) had greater within-field pollen in the control field than in the border field; this may be due to differences in timing of maximum shed. Spatial patterns of accumulated daily observed (Figure 4.3) deposition reveal similar dispersive plumes for the border and control field, with greater downwind dispersal for the windier cases (Figure 4.2). The control field has more dispersal far from the field, with less mid-range dispersal (note that the log 10 scaling highlights the difference in the far-field and reduces the differences near the field).

Spatial patterns of accumulated daily simulated deposition (Figure 4.4) are broadly similar to the observed deposition for each field, with a long-range dispersive tail and a sharp
gradient near the field. However, the simulated deposition pattern is wider, with greater deposition at greater distances from the field (highlighted by the base-10 log scaling); this error is especially acute on August 14, which had the lowest observed wind speed. There is also slightly less deposited pollen at mid-distances from the field (~50 m to 100 m).

An interesting error occurs in the August 10 case, in which the deposition plume is displaced to the north of the observed maximum deposition. The wind direction shifted during the morning from NE to ENE, so greater pollen shed earlier in the day would explain the error. The deposition pattern from 800 LST alone much more closely matches the observations (Figure 4.5). The observed wind speed was higher than is typical in the morning (~2 m s\(^{-1}\) at 800 LST). This highlights the need for more research on the sensitivity of the diurnal pollen shed pattern to environmental factors, particularly wind speed.

Difference plots of simulated and observed deposition, which are not on a logarithmic scale, principally highlight model errors near the field edge (Figure 4.6). The error primarily occurs with relatively windy cases due to near-field locations with high model deposition and substantially less observed deposition. Although there may be biases in the predicted wind field, modest changes to the flow properties would not correct this near field error in most cases. The near field error may be minimized by reducing simulated shed from the field edge, but there is no concrete reason to suspect that field edge pollen shed was reduced.

Downwind transects for each day (Figure 4.7) illustrate that the model captured the sharp gradient of deposition near the source, but deposition far from the field tended to be over-predicted. The greatest error is (again) on with the August 14 case. The observed deposition, with no pollen at several locations and small amounts at a few locations, suggests that some of the difference between observed and simulated deposition may be due to the
problems in sampling observed pollen far from the field. The August 10 result is unique, since the model under-predicts deposition for much of the downwind transect of each field. This is likely explained by the aforementioned error in the location of maximum downwind pollen; the west transect (not shown) illustrates a corresponding deposition over-prediction.

The model-produced patterns of deposition for the border and control fields are similar (Figure 4.4). The border field has modestly (~3.5%) less maximum within-field deposition on August 10 and 14, due to the reduction in wind speed over the field. The border field also has a slightly sharper downwind decrease in deposition with distance (within ~100 m of the field). This difference in deposition is also due to the reduced low-level wind speed associated with the downwind border. The deposition of the control and border field is similar far from the field, with slightly more pollen downwind of the control field.

4.5 Analysis of flow properties

Weather stations were placed within the maize plots, roughly 15 m from the southern edge. The wind observations, at a height of 1.5 m, show an obvious wind reduction inside the fields (Figure 4.8). While the reduction varies in time (sensitive primarily to upstream wind speed), the control field has a wind speed reduction of ~0.5 ms\(^{-1}\) while the border field has reduction of ~1 ms\(^{-1}\). This is consistent with the observations in Clark et al. (2007), in which taller maize generated a wind speed reduction up to roughly 1 ms\(^{-1}\).

The simulated flow fields for the control field are similar to the analogous maize field surrounded by soybean case discussed in Arritt et al. (2007) and Clark et al. (2007). The maize field reduces the wind speed and increases TKE as an internal boundary layer develops. The horizontal wind convergence generates an updraft over the field, with a
placement determined largely by wind speed; higher wind speeds shift the peak upward vertical velocity toward the downwind field edge. Since the observed wind speed and direction vary substantially over the period, it is useful to consider the idealized case of direct westerly flow. Consistent with the observations, the addition of the sorghum border reduces the wind speed by \( \sim 1 \text{ ms}^{-1} \) over much of the maize field (Figure 4.9). There is a reduction in wind speed in the lee of the border field, as the border slows the wind in the downwind region of soybean. The TKE field is augmented near the borders, with an additional enhancement at low levels downwind of the maize field. The TKE increase near the borders is increased substantially for sensitivity tests with much taller borders (not shown), since the taller border encounters greater wind speeds.

Most of the time, the flow is not perpendicular to the field. The simulated flow behavior and sensitivity to the border is similar to the idealized case for the hour ending 11:00 LST on 09 August (Figure 4.10). With upstream flow of \( 2.4 \text{ ms}^{-1} \) at 209° (SSW), the behavior is qualitatively similar to the simplified case above. The wind speed is decreased over the field, due to both the maize and the border. The border again enhances the wind speed reduction at and beyond the upwind border. The impact of the downwind border is clearly seen, as the wind recovery in the lee of the maize field is interrupted by the field. For this relatively windy case, this protected zone is well behind the border.

The comparison of simulated horizontal wind with the wind observations is complicated by the sharp gradients evident on Figures 4.9 and 4.10. Nonetheless, the model sensitivity to the maize and border is broadly consistent with the field observations. The simulated flow features a wind speed reduction of \( \sim 1 \text{ ms}^{-1} \) relative to the upstream flow near and just below the top of the maize canopy. The border further reduces the wind speed
compared with the control field, with a reduction between 0.5 and 1 ms\(^{-1}\) near the top of the canopy, which is generally consistent with the observations.

### 4.6 Sensitivity to shelter characteristics, shed, and location of observations

Arritt et al. (2007, paper 1) and Clark et al. (2007, paper 2) discussed the impacts of the soybean to maize transition pollen dispersal. The reduction in wind speed over the maize field reduced dispersal away from the field, while the field-induced vertical velocity and altered TKE slightly increased long-range dispersal. In the present study, we explore the sensitivity in the case of the added sorghum border. A test LPD simulation using the upwind flow for the entire domain (i.e. without the effect of the sorghum border and maize on the flow) generates less deposition within the field, as well as substantially more deposition for most of the downwind transect (Figure 4.11). This is a larger impact than the difference between the control and border simulations, revealing again that the maize field itself modifies the flow. Simulations including the impact of the border and sorghum on the wind speed, but with vertical velocity set to zero and upwind TKE, show a modest sensitivity consistent with the results in Clark et al. (2007) without a border (Figure 4.13). A simulation with a taller sorghum border (3.7 m) demonstrates a small sensitivity to border height, with only modest changes to the downwind dispersal (Figure 4.12).

Since there is a very sharp decrease in deposition with distance close to the field, we tested the sensitivity to a reduction in pollen shed at the edges of the field by not releasing pollen within the last 4 m on all sides. The resulting deposition within the field was not meaningfully affected, but the deposition downwind from the field was modestly reduced along the entire transect (Figure 4.13). The greatest reduction was near the field, with a ~20%
reduction. Since the sorghum border surrounds the maize field, the trap locations of the border field are slightly farther from the pollen shed than the analogous control locations; an LPD sensitivity test using the border field flow fields and control field locations reveals an increase in near-field deposition, but little difference at greater distances from the field (Figure 4.13). While the transect profiles are slightly different, they do not explain the differences in the observed or simulated border and control fields.

4.7 Conclusions

A 2005 field study in Iowa explored maize pollen deposition with two research plots, one of which was surrounded by a ~1 m taller sorghum border. Although the differences between the fields are moderate, the observed border field pollen deposition is generally less at large distances downwind of the field, with greater pollen at mid-range distances from the field. In order to explore the sensitivity of pollen deposition to the maize field and border, a three-dimension Lagrangian model of maize pollen dispersion has been coupled with the Wang Takle (WT) shelterbelt model. Using single point upwind observations to initialize the shelterbelt model and subsequently drive the LPD, simulations were run for each hour and used to generate scaled daily composites of deposited model pollen valid at the observed locations.

The model captured the sharp deposition gradient near the source field and produced a realistic dispersive tail of low deposition at greater distances from the field. The simulations generally produced too much pollen at large downwind distances from the field. In addition to model deficiencies, this error may be in part explained by sampling issues, since the sampled simulated region is much larger than the size of the pollen traps. However, the maximum observed pollen deposition was ~20 grains cm\(^{-2}\), while the maximum
simulated deposition was ~1 grain m$^{-2}$. Given the greater peak observed deposition, it is unlikely that sampling issues adequately explain the model error far from the field. It is still likely that the trap sampling far from the field emphasizes the model error by reducing the probability of sampling the small amount of observed pollen far from the field. For the new dispersion simulations using the scaling flow fields, the simulated pollen far from the field is reduced just enough that many of the sub samples have zero deposition.

There may also be errors with the simulated flow fields, though the predicted wind speeds are consistent with the available (although spatially limited) observations. Generating the upwind profiles from single point wind measurements also introduces error. The necessary assumption that the unperturbed flow is in balance with the soybean surface is difficult to assess. However, the simulated deposition is not highly sensitive to small changes in wind speed or somewhat larger changes in vertical velocity and TKE (as in the sensitivity tests using zero vertical velocity and unperturbed TKE).

Consistent with Arritt et al. (2007), the maize field affects pollen flow through a reduction in horizontal wind speed, increased TKE at and above the field, induced vertical motion, and the development of an internal boundary layer. The addition of the sorghum border enhances the reduction in horizontal wind speed, as well as (more modestly) altering the turbulence and vertical velocity. The border field generates more pollen deposition over the field than the control simulation, with a corresponding reduction in downwind pollen. The simulated differences far downwind of the field are small in relative terms, but large in relative terms (up to 50% in some cases). The deposition change due to the border is primarily due to changes to the mean wind speed, though vertical velocity and TKE do have some simulated effect.
The results are largely insensitive to border porosity, width and height. Simulations with a taller sorghum border (3.7 m, instead of 2.7 m) produce only small changes from the shorter border field simulation. In addition, the maize field itself provides its own shelter and has a larger effect than the surrounding border. Simulations without the effect of the maize or border on the flow result in substantially more downwind pollen than any of the other simulations, especially close to the field. A remaining question is the effect of a field-edge border on dispersal in the case of neighboring maize fields, with no soybean/maize contrast. The border will have an impact near the shelter, but will likely differ from the sensitivity studied here and may be a function of field size. Test simulations (not shown) without the soybean/maize contrast generate a large border-induced reduction in near-field deposition, with a small effect at distances greater than ~200 m. We suggest further research to explore the sensitivity of the dispersion to different types of field edge vegetation contrasts and borders.

For most cases, the simulated deposition is not very sensitive to the assumed diurnal shed distribution. For example, a non-weighted average of each hourly simulation does not change the results substantially for any of the presented cases. However, it appears that peak shed occurred much earlier than usual on August 10; this earlier peak may have been due to relatively high morning wind speeds. In any case, the hour 1 simulated deposition much more closely matches the observed deposition than do results integrated over the entire day. This highlights the need for greater research on the dependence of the diurnal pollen shed pattern to wind speed and other environmental factors.
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4.9 References


4.10 Figures

Receptor Locations

Figure 4.1. Receptor locations during the August 2005 field experiment. The rectangle indicates the source field. The locations are defined with $y = 0$ at the southernmost location and $x = 0$ at the westernmost location.
Figure 4.2. Wind roses for 9, 10, and 14 August 2005.
Figure 4.3. Logarithm (base 10) of observed pollen deposition on 9, 10, and 14 August 2005 for the control and border fields.
Figure 4.4. Logarithm (base 10) of simulated pollen deposition on 9, 10, and 14 August 2005 for the control and border fields.
Figure 4.5. Difference between simulated and observed scaled deposition on 9, 10, and 14 August 2005 for the control and border fields.
Figure 4.6. Logarithm (base 10) of 0800 LST simulated pollen deposition on 10 August 2005 for the border field.
Figure 4.7. Transects in the downwind direction of the logarithm (base 10) of observed (solid) and simulated (dashed) control and border field pollen deposition for 9, 10, and 14 August.
Figure 4.8. 09 and 10 August observed wind speed at upwind, border field, and control field locations.
Figure 4.9. Simulated u component of the wind, TKE, and vertical velocity with 2 ms\(^{-1}\) upstream westerly flow at a height of 1.5 m, valid in the middle of the domain (y=350 m) for border field (left) and the control-border difference between fields (right).
Figure 4.10. Simulated border field horizontal wind component and, control – border field (N-S) u, v, w, and TKE cross-sections for the hour ending 09 August 1100 LST, valid in the middle of the domain (x=350 m).
Figure 4.11. Transects in the downwind direction of the logarithm (base 10) of observed and simulated deposition for 10 August, including simulations using upstream flow, upstream TKE, and vertical velocity set to 0.
Figure 4.12. Transects in the downwind direction of the logarithm (base 10) of observed and simulated deposition for 10 August, including a simulation with a taller Sorghum border.
Figure 4.13. Transects in the downwind direction of the logarithm (base 10) of observed and simulated deposition for 10 August, including simulations with reduced pollen shed at field edge, and deposition valid at north field locations.
CHAPTER 5. GENERAL CONCLUSIONS

5.1 General discussion

The Lagrangian particle (LPD) approach is attractive for simulating maize pollen dispersal, since it can be used in complex flow regimes and allows tracking of each pollen grain. A three-dimensional LPD of maize pollen dispersion has been developed and tested using field data collected in central Iowa during August 2003 and northwest Iowa in 2005. In both field experiments, small maize plots were surrounded by soybean. This roughness transition generated complex flow fields, with a reduction of wind speed within and above the maize canopy, development of an internal boundary layer, increased turbulent kinetic energy near the top of the maize, and rising motion over a portion of the field. In the 2005 experiment, there was an additional maize field surrounded by a border of sorghum. The border results in additional wind protection, as well as changes in TKE and vertical velocity.

Scaling relationships in the atmospheric surface layer were used to generate the flow fields required by the LPD in paper 1, with additional adjustments for canopy flow and the roughness transition from soybean to maize. The model captured the sharp deposition gradient near the source field, as well as a dispersive tail of low deposition at greater distances from the field. There was a tendency for the simulations to deposit too much pollen very close to the field; some of the error was likely due to the use of scaling relationships for flow fields, as well as the lack of model replication of potential within-field variations in pollen shed (the within-field observed deposition varied substantially more than the simulated deposition). Limitations on the number of particles released may have led to problems in detection of model deposition far from the field.
Although the use of empirical relationships to adjust for the canopy and roughness transition is a simplification, model deposition error was much less than if only the upwind wind profile was used. There was additional improvement in model accuracy with the inclusion of vertical motions estimated using the incompressible continuity of mass. This motivated the 3D implementation of the Wang and Takle (WT) shelterbelt model to provide physically consistent flow fields and allow further analysis of the importance of the maize-field altered flow for the 2003 field configuration (paper 2). Using the model for the flow fields and generating a large ensemble of simulated pollen resulted in a somewhat smoother deposition pattern; the model captured the sharp deposition gradient near the source field and dispersive tail of low deposition, but tended to deposit too much pollen at large distances downwind of the field. Some of error may be due to an inability to include within-field variations in pollen shed; however, scaling to field mean rather than maximum deposition did not have a large qualitative effect on the results.

Exploration of sub-samples allows the assessment of deposition variability at the observed locations. This is useful for assessment of both model performance and outcross risk. This sample variability is maximized within and near the field, while the relative variability is greater at large downwind distances. Of interest, the model bias is systematic among most ensemble members. Although the model performance is not objectively better than with the scaling-based flow fields in paper 1, the use of WT is preferred since it provides physically consistent flow. Simulations with the scaling flow fields and greater pollen release reduce the difference between the sets of 2003 model results.

Using the WT flow fields, sensitivity tests revealed that the field-induced vertical velocity decreased within-field deposition and increased deposition out to moderate distances
(~50 to 100 m) from the field. The increase in TKE above the canopy also fostered dispersion away from the field. The relative impacts of horizontal flow, vertical velocity, and TKE may be sensitive to field configuration, but simulations indicate that the changes in horizontal flow are dominant.

The effect of the maize field as a shelter to the approaching flow raises the possibility that additional shelter may reduce pollen dispersal away from the field. This was explored in paper 3, for which WT flow fields were used to drive LPD simulations and compared to field measurements from the 2005 field experiment. The 2005 experiment had added an additional 2.7 m tall sorghum border surrounding the field, as well as a control field without the border; soybean surrounded the maize plots in both cases, as in the 2003 field study. Although the differences were modest, the observed control field pollen deposition was generally greater than the border field well downwind of the field, with less pollen at mid-range distances from the field.

As in the 2003 cases, model simulations captured the sharp deposition gradient near the source field and produced a realistic dispersive tail of low deposition at greater distances from the field. Consistent with the model bias in paper 2, the simulations generally produced too much pollen at large downwind distances from the field. In addition to model deficiencies, this error may be partially explained by sampling issues. The sampled simulated pollen count region of 2 x 2 m is much larger than the size of the pollen traps (6 x 6 cm). A reduction in model count region reduces the likelihood of any deposition far from the field; modest changes in count region do not correct this bias, however. There may also be errors with the simulated flow fields, although they are consistent with the available (spatially
limited) observations. However, the simulated deposition is not highly sensitive to small changes in wind speed or somewhat large changes in vertical velocity and TKE.

Consistent with the 2003 cases, the maize field affected pollen flow through a reduction in horizontal wind speed, augmented TKE at and above the field, updraft with location sensitive to upstream velocity, and the development of an internal boundary layer. The additional border enhanced the reduction in horizontal wind speed near the height of the maize and also reduced the wind speed beyond of the downwind border. The sorghum border also modestly altered the turbulence and vertical velocity (note that a much taller simulated border increased TKE substantially).

The simulated border-protected field deposited modestly more pollen over the field, along with a corresponding reduction in downwind pollen. The differences far downwind of the field were small in magnitude, but could potentially impact the probability of outcross. The simulated deposition change due to the border was dominated by the changes to the mean wind, though vertical velocity and TKE did have some effect.

The results were largely insensitive to border porosity, width and height. Simulations with a 3.7 m sorghum border produced only small changes from the border field simulation. While the border had a meaningful affect on the simulated flow fields and dispersal, the effect of the change in roughness from the soybean/maize contrast maize also had an impact. Simulations using the upwind flow over the entire model domain resulted in substantially more downwind pollen than any of the other simulations, especially close to the field. Thus, both the soybean/maize surface contrast and sorghum border substantially reduced pollen deposition near the field, with a small impact at larger distances from the field.
5.2 Recommendations for future research

Several research hypotheses are natural outgrowths of the dispersion modeling presented here. Research questions include:

1. The hypothesis that a field-edge border reduces much longer-range dispersal and subsequent risk of outcross should be tested. The results in paper 3 demonstrate some reduction in dispersal for the border field. However, the magnitude of the difference is small at large distances (~150 m) from the field. This raises questions about the impact on much longer-range dispersal and potential outcross. Field data is invaluable, but practical considerations make these measurements far from the field difficult. Numerical simulations may be used, with large amounts of pollen released and a larger domain. Model results could then aid in outcross risk assessment.

2. The hypothesis that a windbreak reduces long-range pollen dispersal in cases without the soybean/maize contrast should be tested. The effect of a field-edge border alone was simulated in paper 3, but should be validated with field data and simulated on a larger scale. Test simulations with borders in the case of uniform maize or soybean (not shown) demonstrate a larger border effect than in the present study at modest distances from the field, while the border effect at distances greater than ~200 m was small. The effectiveness of a border in the case of otherwise a homogeneous maize field is also likely a function of field size, with large fields being impacted less than small research plots.
3. The hypothesis that the diurnal pollen shed pattern is sensitive to meteorological conditions, such as temperature, relative humidity, and wind speed, should be tested. In many of the cases studied here, alterations in the daily scaling would not affect model performance; however, at least one of the cases had model error that could be explained by earlier than usual pollen shed.

4. The hypothesis that dispersal is insensitive to border characteristics should be tested. The results in paper three suggest that modest changes in border height and width had negligible effect on the results. This should be explored with additional tests and (ideally) validated against field data.

5.3 References


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