Tracking the potato late blight pathogen in the atmosphere using unmanned aerial vehicles and Lagrangian modeling

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ABSTRACT

A means for determining the aerial concentration, C (sporangia m^{-3}), of plant pathogenic spores at various distances from a source of inoculum is needed to quantify the potential spread of a plant disease. Values of C for *Phytophthora infestans* sporangia released from an area source of diseased plants in a potato canopy was quantified in three ways: (1) by using Rotorods to sample the air just above the source, (2) by using unmanned aerial vehicles to sample the air at altitudes up to 90 m above the source and at downwind distances up to 500 m from the source, and (3) by using a Lagrangian stochastic simulation of sporangia flight trajectories to tie these two measurements together. Experiments were conducted using three potato crops over two years. Model predictions of time-average, crosswind-integrated concentrations were highly correlated ($r = 0.9$) with values of C measured using the unmanned aerial vehicles. The model describes the release and dispersal of sporangia from a potato canopy to a downwind distance of 500 m. Thus, it may have utility as a part of an area-wide decision support system by helping to predict risk of disease spread between neighboring or distant potato fields.

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1. Introduction

Late blight, caused by *Phytophthora infestans* (Mont.) de Bary, is a devastating disease of potatoes and tomatoes whose control depends heavily on chemical pesticides. Although weather can be a dominant factor in the development of late blight epidemics, the disease will not develop if the pathogen is not present in an area. Methods for predicting the risk of infection will make it possible to develop more effective strategies for controlling late blight with fewer applications of chemical pesticides. Aerial transport of inoculum between fields has long been suspected but has not been quantified; therefore the impact of aerial transport as a risk factor is not well understood.

Phytophthora infestans produces deciduous asexual sporangia that are dispersed through the atmosphere to susceptible host species (Hirst and Stedman, 1960; Schumann and D'Arcy, 2000). The sporangia may survive from one to several hours in the atmosphere, depending on their cumulative exposure to varying degrees of solar radiation (Mizubuti et al., 2000; Suneri et al., 2002). Once

deposited on plant surfaces, viable sporangia germinate and invade host tissues (Schumann and D'Arcy, 2000). Several days after infection, new sporangia are produced and the cycle of aerial dispersal and infection is repeated.

The aerial transport of *P. infestans* sporangia to potato or tomato fields from off-farm sources presents a potential risk of crop loss due to late blight infection that may preclude full implementation of integrated pest management practices (Skelsey et al., 2008b, 2009). In addition, new, more aggressive strains of *P. infestans* could be introduced into the United States from other parts of the world (Fry and Goodwin, 1997; Fry et al., 1992, 1993), and these new strains might be transported ten's of kilometers (Aylor, 2003) through the atmosphere to new geographical locations. Late blight re-emerged in the United States in the 1990s as a serious disease of potato and tomato, mainly due to the introduction of new, more aggressive strains of the pathogen, particularly of the US-8 clonal lineage and the second mating type (A2) (Fry and Goodwin, 1997; Fry et al., 1993; Goodwin, 1997; Goodwin et al., 1994; Goodwin and Drench, 1997; Kato et al., 1997; Lambert and Currier, 1997). It is believed that significant aerial dispersal of these new strains of *P. infestans* contributed to rapid, widespread epidemics of late blight in the United States (Aylor et al., 2001; Campbell, 1999; Fry and Goodwin, 1997). The continuing importance of the pathogen to

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agriculture was underscored in 2009, when late blight was found in several U.S. states and was the most widespread in the U.S. in recent history (Hu et al., 2010).

An improved understanding of the aerial dispersal of *P. infestans* sporangia will help predict infection probabilities and improve management of late blight through integrated use of sanitation, scouting, weather forecasting, resistant varieties, fungicides, and computer simulations. Currently lacking is a method to quantitatively predict whether sporangia from an outside source will be transported to a specific field and initiate disease. This information can be integrated as part of a decision support system and be evaluated along with the other ways that the pathogen could occur in a field, i.e., via infected tubers, either surviving from the previous year or unintentionally planted (Johnson, 2010), or from oospores (Flier et al., 2001; Mizubuti et al., 2000).

The risk of late blight infection due to aerial transport of sporangia depends on several factors including: (1) the number of *P. infestans* sporangia available for dispersal at any given time; (2) the fraction of those available sporangia that become airborne; (3) the dilution of sporangia by the wind and their removal from the air by deposition processes; (4) the survival of sporangia during flight; (5) the efficiency of deposition of sporangia on susceptible tissue; and (6) the amount of susceptible host tissue per unit ground area (Aylor, 1986; Skelsey et al., 2008b). Although a general framework for aerial transport of *P. infestans* sporangia exists, quantitative methods are needed to incorporate these factors into models for assessing risk of infection from aerially dispersed sporangia.

Only a few studies (mostly based on modeling or on circumstantial evidence) have suggested the distance that the sporangia could be dispersed through the atmosphere (Aylor, 2003; Harrison, 1992; Skelsey et al., 2008a,b; Suneri et al., 2002; Van Der Zaag, 1956). A wide-spread late blight infection on tomatoes in central New York State in 1993 suggested dispersal over distances of 40–60 km range from a putative disease focus (Fry and Goodwin, 1997). However, detailed scouting for a more general source was not conducted and, as far as we are aware, there have been no published studies that have actually quantified the dispersal of *P. infestans* sporangia over such long distances. Although most sporangia are likely deposited within a few meters of their source (Waggoner, 1952), some can be dispersed by the wind much farther, and perhaps over distances of several kilometers (Hirst and Stedman, 1960; Skelsey et al., 2008a). Because there are very few quantitative measurements of the dispersal of *P. infestans* sporangia beyond a few meters from a source, there is a need to quantify dispersal of sporangia to greater distances and heights in the atmosphere. To help fill this gap, we present measurements of *P. infestans* sporangia dispersal at altitudes up to 90 m above and at downwind distances up to 500 m from sources, and we employ a quantitative model of atmospheric transport of spores to interpret these measurements.

2. Materials and methods

2.1. Crop and inoculum source

Field experiments were conducted in July 2008 and in August of 2008 and 2009 at Virginia Tech's Kentland Research Farm in Blacksburg, Virginia. A 0.63 ha field of the potato cultivar Katahdin (Fig. 1, Field A) was planted on 5 May 2008 and a 0.65 ha field of the potato cultivar NY118 (Fig. 1, Field B) was planted 7–8 May 2008. A 1 ha field of cultivar Katahdin (Fig. 1, Field C) was planted on 14 May 2009. At planting, fertilizer was applied at a rate of 1347 kg/ha (10–10–10 N–P–K in 2008, and 10–10–20 N–P–K + 3.34 kg/ha Boron in 2009). Plants were hilled on 16 June 2008 (Field A), 17 June 2008 (Field B), and 21 June 2009 (Field C). The distance between rows was 0.86 m for all three fields, and plants were spaced approximately
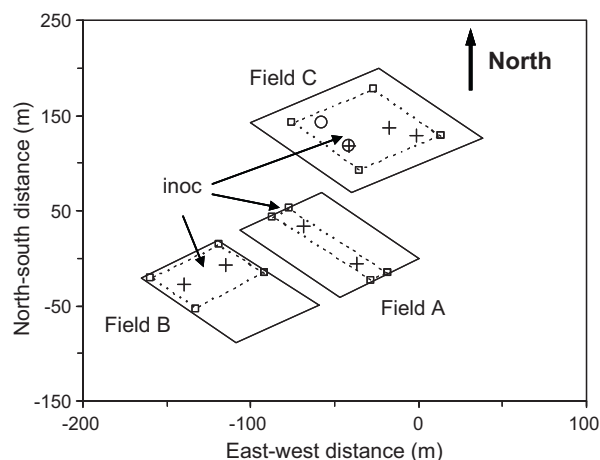

Fig. 1. Layout of the three experimental fields (A, B, and C) used in the present study. Field A was planted to cv Kathadin and tests were conducted in July 2008; Field B was planted to cv NY118 and tests were conducted in August 2008; Field C was planted to Kathadin and tests were conducted in August 2009. For each plot, the planted area is circumscribed by a solid line and the inoculated (source) area is circumscribed by a dashed line. Rotorod tower locations are shown by an ×. In Field C the one tower with an × inside a circle was moved to the position shown by the open circle on 14 August 2009.

0.37–0.40 m apart within the row. Applications of herbicides, insecticides, and fungicides were applied following standard agronomic practices.

The experimental potato plots were approximately square and were planted to a single cultivar in approximately north-south rows in 2008 and in east-west rows in 2009 (Fig. 1). In Field A 16, 90-m long rows were inoculated on 8 July 2008. In Field B, the top half consisting of 106, 45-m long rows were inoculated on 1 August 2008. In Field C, an area of 61 by 64 m was inoculated on 27 and 29 July 2009 and 3 August 2009. The area immediately surrounding the fields was almost flat and there were no obstacles to the wind near the field for ~100 m in the west, south and east directions, however, there was a 10 m high hill located about 20 m to the north of the northern edge of the plot. Wind directions from the north occurred only occasionally during the experiments (Fig. 2).

Two different sources of *P. infestans* were used in the experiments. Transport and handling of the strains used in the 2008 and 2009 experiments were conducted under USDA-APHIS permit P526P-07-04420. Release of the strain in 2009 was conducted under USDA-APHIS P526P-09-02395. In 2008, strain US06001 (Fry Lab, Cornell University, A2 mating type, US-8 genotype) was used to inoculate Fields A and B. In 2009, strain Pi8 (Schmale Lab, Virginia Polytechnic Institute and State University, A2 mating type, US-22 genotype) was used to inoculate Field C. Sporangia were produced in the laboratory on surface disinfested foliage from potatoes (2008 and 2009) and tomatoes (2009). The inoculum was prepared
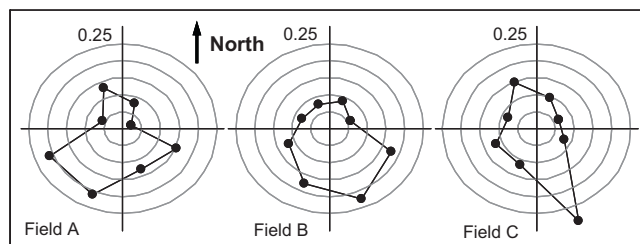

Fig. 2. Fraction of the time that the wind direction was from a particular 45° sector during 0800–1400 DST (1200–1800 UTC) for the experiment in Fields A (July 2008), B (August 2008), and C (August 2009). The scale is given by the concentric circles with radii spaced at 0.05 intervals.