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FULL RESEARCH PAPER

A dynamic model forecasting infection of pear leaves by conidia of *Venturia nashicola* and its evaluation in unsprayed orchards

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Abstract A dynamic model, called VenInf, was developed to forecast infection of pear leaves by conidia of *Venturia nashicola*. By simulating conidial infection processes following a rain event, the model estimates % conidia that successfully infected leaves at the end of an infection period. The model is mainly derived from logistic models developed from recent laboratory and glasshouse experimental results on infection of pear seedlings to estimate the rates of infection and mortality. It simulates the conidial infection process at 5 min intervals using temperature, relative humidity (RH), surface wetness and rainfall as input. The model was evaluated against pear scab in four unsprayed orchards in China over a 4-year period. In all orchards, all significant disease increases were associated with infection periods predicted by the model. In one orchard, in 2004 the incidence of leaf infection remained very low (<3%) during the entire season despite the model forecasting several severe infection periods. Results of orchard evaluation suggest that the model is able to identify all important potential infection periods. Thus, further field studies should be carried out to determine whether and how the model can be used in practice to assist farmers in making decisions on fungicide applications.

Keywords Pear scab · Forecasting model · Orchard evaluation · Conidial infection

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Introduction

Pear scab, caused by *Venturia nashicola* (Tanaka and Yamamoto 1964), is an economically important disease in China, especially in traditional Chinese pear varieties (Luo 1983). Conidia are considered the main source of inoculum in primary and secondary infection in most areas of north China (Li 1959; Yin and Yu 1988). Recent research has obtained a body of quantitative data on infection of leaves by *V. nashicola* conidia, which are sufficient to develop a model forecasting infection of pear leaves. Conidia of pear scab germinate at temperatures ranging from 2 to 30°C and require free water or near saturation moisture levels (Luo 1983; Umemoto 1991; Li et al. 2003). The relationship between lesion development on leaves and duration of wetness can be described by logistic models for temperatures in the range of

5–25°C. The effects of temperature on the rate and maximum disease parameters of the logistic model were well represented by polynomial models (Li et al. 2005). Dry periods interrupting a wetness period may cause mortality of conidia with the rate of mortality depending on temperature during the dry periods (Li et al. 2005). These findings provide sufficient quantitative epidemiological data of pear scab needed to develop a model predicting disease risks using climatic variables.

Currently, pear scab is controlled mainly by scheduled application of fungicides irrespective of disease risks. In order to reduce fungicide input while maintaining satisfactory disease control, there is a need to develop an accurate model for forecasting infection of pear leaves by the pathogen, especially during the early season. For apple scab, several models have been developed to forecast infection and are used in practice (Xu et al. 1995; MacHardy 1996; Holb et al. 2005b). The use of such models led to effective management of the disease and a reduction in fungicide input in England (Berrie and Xu 2003). As pear scab is similar to apple scab in disease development and epidemics, a forecast model for pear scab could also be similarly successful.

In this paper, we describe the details of a dynamic model, called VenInf, for forecasting the risks of pear scab infection and the evaluation of results obtained in four unsprayed orchards in China. This model was developed from the recent data obtained in laboratory and glasshouse experiments (Li et al. 2003, 2005) to forecast the infection of pear leaves by *V. nashicola* conidia following a rain event. Epidemics of pear scab were monitored in four unsprayed orchards over a period of 4 years (2002–2005) in China and these field data were then used to evaluate the accuracy of predictions given by the model.

Materials and methods

Model description

Overview of the model

VenInf simulates infection of young pear leaves by *V. nashicola* conidia following a rain event. An infection period was initiated once an accumulated rainfall during a continuous rain event exceeded a predefined threshold and terminated once there were no more infective conidia remaining. During the infection process, conidial mortality was also taken into account. The model estimates % conidia that had successfully infected leaves at the end of each infection period.

Figure 1 shows a simplified flow diagram of VenInf and Table 1 lists key variables used in the model. VenInf is based on the logistic model for conidial infection, expressed in a discrete form as

$$Y_t = Y_{t-1} + \Delta Y = Y_{t-1} + RY_{t-1}(K - Y_{t-1} - TD_t)\Delta t \quad (1)$$

where Y_t and Y_{t-1} are % conidia that successfully infected leaves at time t and $t-1$, respectively, ΔY is % conidia that had infected leaves during $t-1$ to t; R is the rate of the logistic model (h^{-1}), K is the maximum infection (i.e., % infected), TD_t is the total % dead conidia from the start of infection to time t, and Δt is the integration step (h). The quantity, $K - Y_{t-1} - TD_t$, estimates % conidia that are viable but had not infected leaves at time t. VenInf estimates the rates of infection and mortality using temperature, relative humidity (RH), surface wetness and rainfall, recorded at intervals $\leq$2 h, as input. VenInf is coded in C# and can be run as a Windows or web programme.

Details of the model

Logistic model describing the dynamics of conidial infection. VenInf is mainly based on logistic models developed from controlled environment experiments (Li et al., 2003, 2005), i.e., the temporal dynamics of infection of pear leaves by conidia at each temperature during a continuous wet period was described by

$$Y = \frac{K_T}{1 + \exp(-R_T(w - M_T))} \quad (2)$$

where Y is % conidia that had infected leaves, w is the length of wetness duration (h); and K_T, M_T and R_T are the maximum % conidia that could have infected leaves, the length of elapsed wetness duration (h) until $Y = K_T/2$, and the rate parameter (h^{-1}) at temperature T (°C). The relationships of T with K_T, M_T and R_T are described by the following models:

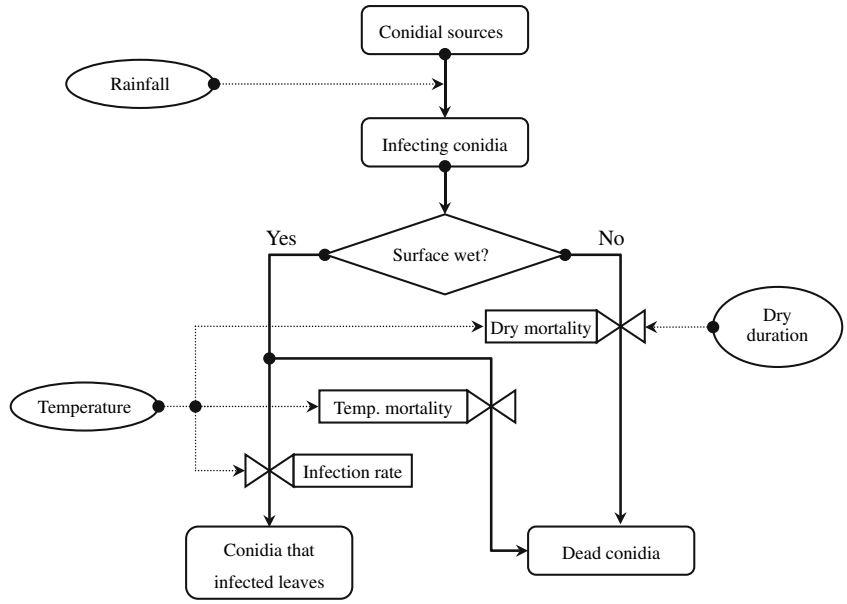

Fig. 1 A simplified diagram of the model simulating conidial infection of pear leaves by *Venturia nashicola* conidia. State variable (rectangular boxes) are linked with rate and switch variables. The surface dry/wet status is jointly determined by rainfall, temperature, RH and wetness sensors (see text for details)

Table 1 Important variables in the model, simulating infection of pear leaves by *Venturia nashicola* conidia

Variables	Description
State variables	
Y_t	% Conidia that had successfully infected leaves at time t
TD_t	% Total dead conidia at time t
Rate variables	
$R_{T(t)}$	Logistic infection rate (h^{-1}) at time t with temperature of T
$D_{T(t)}$	Percentage of infecting conidia that died due to temperature in the last time step (Δt) during wet periods
$D_{D(t)}$	Mortality rate (h^{-1}) of conidia during dry periods at time t
Driving variable	
$T(t)$	Temperature (°C) at time t
$W(t)$	Leaf wetness (%) at time t
$RH(t)$	RH (%) at time t
$TR(t)$	Accumulated rainfall (mm) during a single continuous rainfall event
Others	
TDL_t	Total length of dry duration (h) at time t
ΔY_t	% Conidia that had infected leaves during the last time step
K_T	Maximum % conidia that could have infected leaves at a given temperature T
M_T	Length of elapsed wetness (h) until $K_T/2$ conidia have infected leaves at a given temperature T

$$K_T = 0.081 + 0.687T^2 - 0.229T^3 \quad (3)$$

$$M_T = 47.8 - 37.7T + 9.63T^2 \quad (4)$$

$$R_T = 0.314T - 0.010T^4 \quad (5)$$

In Eqs. (3–5), temperature (T) was scaled down by a factor of 10. Equation (3) was rescaled such that K_T was 1.0 at the optimum temperature (ca. 20°C).

Starting an infection period. Rain triggers an infection period by dispersing conidia from sporulating lesions to young healthy susceptible leaves and providing free water needed for infection. An infection period is initiated once the accumulated rainfall (*TR*) during a continuous wet period exceeded 1 mm unless there is already an ongoing infection process. If *TR* is <1 mm within a continuous period of 2 h, it is set to zero. Biologically, % conidia that had infected leaves at the beginning of an infection period (Y_0) should be zero. Nevertheless, the logistic model (Eq. 1) requires a non-zero value as an initial value. Y_0 is calculated as:

$$Y_0 = \frac{1}{\exp\left(R_{T_0} M_{T_0}\right) - 1} \tag{6}$$

where R_{T_0} and M_{T_0} are logistic model parameters, derived from Eqs. (4–5) with the temperature at the start of an infection period being T_0.

Conidial mortality. There are two types of spore mortality considered in VenInf. Previous results showed that the maximum % spore germination (Li et al. 2003) or the number of lesions on leaves (Li et al. 2005) varied considerably with temperature even during a continuous wet period. Namely, K_T was much less at extreme temperatures, particularly at higher temperatures. VenInf considers that this difference in K_T under continuous wet conditions between temperatures was due to spore mortality caused by unfavourable temperature. This mortality during wet periods is hereafter called temperature mortality. The second type of mortality refers to conidial death incurred during dry periods interrupting an infection period, which is referred to as dry mortality. The key difference between the two mortality types is that temperature mortality occurs during a wet period while the dry mortality takes place during dry periods.

Temperature mortality. If the maximum infection (K_T) during continuous wet conditions represents the infection outcome from all viable conidia, then the rate of temperature mortality can be estimated from Eq. (3). Conidial mortality is assumed to take place from the beginning of an infection period. An infection period is assumed to have completed (i.e., K_T is reached) by the time of $2M_T$ where M_T is estimated from Eq. (4) for a given temperature (T). Assuming a constant rate of temperature mortality for a given temperature, temperature mortality (D_T) during a single time step (Δt) can be estimated from the following equation

$$(1 - D_T)^{2M_T/\Delta t} SI = K_T \tag{7}$$

where SI is the total initial inoculum at the beginning of an infection period and is set to 1.0 (i.e., 100% of viable conidia). Thus

$$D_T = 1 - K_T^{\Delta t/2M_T} \tag{8}$$

During dry periods interrupting an infection period, D_T is set to zero.

Dry mortality. Conidial mortality during dry periods interrupting an infection period was shown to be related to temperature and length of dry duration (Li et al. 2005). From controlled inoculation experiments (Li et al. 2005), the rate (D_D, h^{-1}) of conidial death due to dry periods is estimated as

$$D_D = \begin{cases} 0.2873 \times 0.7503^{TLD_t} & \text{when } T \le 26^{\circ}\text{C} \\ 0.7592 \times 0.4680^{TLD_t} & \text{when } T > 26^{\circ}\text{C} \end{cases} \tag{9}$$

where TLD_t is the total length of a single dry period (h) at time t. Under wet conditions, D_D is set to zero.

The total spore mortality from the start of infection to time t is then calculated as

$$TD_t = TD_{t-1} + (\Delta t D_D + D_T) Y_{t-1} \tag{10}$$

At the start of infection, $TD_0 = 0$.

Calculating percentage of conidia that had successfully infected leaves. During wet conditions, the rate (R_T) of infection is estimated from Eq. (5); during dry conditions, $R_T = 0$. The % new infected conidia during the last time step (Δt) is calculated as

$$\Delta Y_t = R_T Y_{t-1} (K_T - Y_{t-1} - TD_t) \Delta t \tag{11}$$

where TD_t is calculated from Eq. (10). Thus total % conidia that had successfully infected leaves at time t is

$$\begin{aligned} Y_t &= Y_{t-1} + \Delta Y_t = Y_{t-1} \\ &\quad + R_T Y_{t-1} (K_T - Y_{t-1} - TD_t) \Delta t \end{aligned} \tag{12}$$

An infection period is terminated if ($K - Y_{t-1} - TD_t$) < 0.1%. In the model, an integration step of 5 min was used, i.e., Δt=1/12. If weather data are recorded at an interval greater than 5 min, the model estimates weather variables using linear interpolation.

Weather variables. The model needs the following weather data: temperature (°C), RH (%), rainfall (mm) and surface wetness; these variables need to be recorded at an interval $\leq$2 h. In addition, vapour pressure deficit (vpd, hPa) is calculated from temperature and RH. The leaf surface is assumed to be wet if one of the following three conditions is met: (1) rainfall during the last time step was $\geq$0.2 mm, (2) the electronic wetness sensor indicated >50% conductivity, and (3) vpd during the last time step is <1.1 hPa. Otherwise, leaves are assumed to be dry.

VenInf simulates the infection of pear leaves by *V. nashicola* conidia at 5-min intervals, i.e., Δt=5 min. If necessary, weather variables were linearly interpolated between recorded data at two scans.

Orchard evaluation of the model

Length of the incubation period

In order to match new lesions with possible infection times for natural epidemics, it is essential to estimate the approximate length of the incubation period (from initial infection to appearance of visible symptoms) in relation to temperature. One-year-old seedlings of pear rootstock (*Pyrus ussuriensis*) were inoculated with a conidial suspension in a poly-tunnel in 2003. Inoculation experiments were conducted on six occasions (3, 16 & 29 May, and 4, 9 & 17 June). For each inoculation, 10 pots of pear seedlings were used and all the leaves in the seedlings were inoculated with a conidial suspension with *c.* 5×10^4 conidia ml^{-1}. The seedlings were then immediately covered with plastic bags after inoculation, to keep leaves wet, and placed in an incubator at 20°C. The seedlings were then moved back to the poly-tunnel 24 h later. Lesions on each leaf were first counted 2–5 days after the first lesion was seen and again about 10 days later. An automatic weather station (Monitor sensors PTY Ltd., Queensland, Australia) was installed just outside the poly-tunnel to record temperature every 30 min. The temperature recorded by the automatic weather station was 2–5°C lower than inside the poly-tunnel at noon.

Two cultivars, Tse-pear and Ya-pear (*Pyrus bretschneideri*), were also inoculated with conidia in an orchard to investigate the length of the incubation period in early 2002 and 2003 seasons. In 2002, leaves of Tse-pear were inoculated during a rainy period on 5 April when pear began to flower. In 2003, leaves of Tse-pear and Ya-pear were inoculated on 17 & 28 April, and 3, 9, 16 & 30 May. The inoculation on 17 April, the pear bloom time, was done while it was raining. The other inoculations were conducted in the early evening; the twigs with inoculated leaves were covered with wet plastic bags for 12 h to keep leaves wet. The numbers of scab lesions were recorded 2–7 days after the first lesion was observed. Temperature was recorded with the automatic station as described above.

Monitoring epidemics of pear scab

Four orchards were selected to monitor epidemics of pear scab from 2002 to 2005 in China. One orchard of cv. Tse-pear was located in Lai-Yang Agricultural College (LYAC, Latitude 36:58N, Longitude 120:42E), Shandong Province; this orchard (orchard 1) was monitored for pear scab from 2002 to 2004. In 2002, another orchard of cv. Tse-pear in Xian Park (Lai-Yang) was also monitored; this orchard (orchard 2) was about ca. 600 m from the first orchard. In 2004–2005, an orchard of cv. Chang-Ba pear (*P. bretschneideri*) in Zhao-Yuan (Shandong Province) was monitored for pear scab development; this orchard (orchard 3) was ca. 100 km north of Lai-Yang. Pear scab was monitored in an orchard (orchard 4) of cv. Dangshan-Su pear (*P. bretschneideri*) in Rou-Gu, Shanxi Province, about 1,600 km west of Lai-Yang. The four orchards did not receive any fungicides during the growing season when scab was monitored.

At the beginning of each season, from 10 to 16 trees in orchards 1–3 and 20 for orchard 4 in Rou-Gu were selected in each orchard using the following scheme. Each orchard was divided approximately into an appropriate number of equal sections/parts and the tree at the centre of each section was selected for monitoring. For orchards 1–3, pear scab was assessed weekly from early May onwards in 2002/2003, and from early June in 2004/2005; for orchard 4, weekly monitoring started from early April in 2003

and 2004, and from late May in 2004. In orchards 1–3, the number of scab lesions was recorded on each assessment for all of the leaves of 8 to 16 randomly selected shoots on each tree: 2 to 4 from each direction (east, south, west and north of the canopy). In orchard 4, 5 shoots, one from each direction (east, south, west, north and middle of the canopy), were selected and labelled at the beginning of each season. The number of scab lesions was counted on each of the top 10 leaves from the labelled shoots. Disease assessment was terminated in late August.

Meteorological data

Automatic weather stations (Monitor sensors PTY Ltd., Queensland, Australia) were used to record weather data. One station was used to log data for orchard 1 & 2 in Lai-Yang: the logger was installed at a height of 1 m inside an orchard in the alley way between two rows of trees, ca. 100 m and 500 m from the orchard 1 & 2, respectively. Similarly a logger was installed at a height of 1 m, ca 600 m from orchard 3 in Zhao-Yuan. Finally, another logger was placed in the alley way at a height of 1 m inside orchard 4 in Rou-Gu. Weather data, including temperature (°C), RH (%), leaf wetness and rainfall (mm, sensitivity is 0.2 mm), were recorded every 30 min.

Results

Incubation period

Inoculated seedlings began to show symptoms and sporulate 21 days after inoculation in the poly-tunnel. On the first assessment (ca. 23–27 days after inoculation), % diseased leaves ranged from 34% to 72% (Table 2). Both the number of lesions and % diseased leaves had increased by the second assessment. The temperature outside the poly-tunnel during the period 3 May to 24 July varied from 2°C to 32°C; the average temperature within the incubation period for each inoculation ranged from 17.0°C to 21.7°C. For field inoculations, the time from inoculation to the time when lesions were first seen did not vary greatly between inoculations. In both years, the leaves of cvs Tse-pear and Ya-pear started to show symptoms 21 days after inoculation and many lesions appeared thereafter. In 2002, the first scab lesion was observed on 30 April following the inoculation on 5 April with the mean temperature of 12.6°C during this period. In 2003, the inoculated leaves on 17 April began to show symptoms on 12 May (Table 3). The average temperatures from the six inoculations to the assessments ranged from 14.2°C to 21.4°C. Thus, the results suggested that under orchard conditions the minimum time from infection to the appearance of visible lesions is ca. 3–4 weeks.

Model evaluation

The monitored epidemics of pear scab in the four orchards were compared with the model predictions. In the 4 years, VenInf forecast a total of 58 potential infection periods for the four orchards from 10 April to 30 July. Among the 58 potential periods, the final % conidia that had infected leaves exceeded 50% on 17 occasions, was between 20% and 50% in 17 cases, between 5% and 20% in 9 cases, and between 1% and 5% in 15 cases (Figs. 2–4).

Lai-Yang

In 2002, weather data were recorded from 24 April in the LYAC orchard. However, the first rain was on 5 April and lasted for about 36 h. At that time, about 20% flower buds had bloomed. The first scab lesion was observed on 30 April. A severe infection (84% conidia had infected leaves) was forecast on 14 May, which probably led to the sharp increase in the number of scab lesions around 10 June (Fig. 2B). In the Xian Park orchard, the first scab lesion was observed on 25 June, which probably resulted from the forecast infection periods during the mid to late May period (Fig. 2A). The level of disease remained very low during the entire season.

In 2003, the first rainfall event occurred on 17 April, at about blossom time. The first scab lesion was observed on 11 May, which was likely to have resulted from infection periods forecast in mid-April (Fig. 2C). The subsequent increase in the number of lesions can be associated with the three forecasted infection periods in June (Fig. 2C).

In 2004, the first rainfall event occurred on 26 April, after blossom, which led to a potential infection period, but with only 3% forecasted infection (Fig. 2D). A severe infection period forecast on 8

Table 2 % Pear leaves with visual symptoms of pear scab and average number of lesions per leaf. Leaves were inoculated with conidia of *Venturia nashicola* at different dates and incubated in a poly-tunnel

Inoculation date	No. of leaves inoculated	First assessment[a]				Second assessment			
		Days from inoculation	No. of lesions per leaf	% Scabbed leaves	Mean temperature (°C)[b]	Days from inoculation	No. of lesions per leaf	% Scabbed leaves	Mean temperature (°C)
3 May 02	93	23	4.7	53.4	17.0	31	9.58	72.07	17.9
16 May 02	96	26	6.3	54.5	20.0	38	8.75	69.57	20.2
29 May 02	92	26	11.9	71.7	21.0	37	12.50	78.69	21.5
4 Jun 02	90	24	11.7	54.4	21.2	34	13.01	71.03	21.7
9 Jun 02	116	24	9.9	52.6	21.5	34	12.54	87.84	21.9
17 Jun 02	107	27	8.2	33.6	22.6	37	11.78	48.41	22.8

[a] The first assessment was done 2–5 days after the first lesion was seen

[b] Mean temperature outside the poly-tunnel from inoculation to the assessment date, which was ca. 2–5°C higher than outside

Table 3 % Leaves of two pear cultivars showing scab lesions after inoculation with conidia of *Venturia nashicola* on different dates in an orchard near Lai-Yang Agricultural College

Inoculation date	Cultivar	Days from inoculation[a]	No. leaves inoculated	No. of lesions per leaves	% Scabbed leaves	Mean temperature (°C)[b]
17 Apr 03	Tse-pear	25	First scab lesion was observed			14.2
28 Apr 03	Ya-pear	26	129	21.9	75.2	16.6
	Tse-pear		66	1.3	36.4	
3 May 03	Ya-pear	30	102	11.4	60.8	17.6
	Tse-pear		130	7.9	79.2	
9 May 03	Ya-pear	32	156	3.0	48.1	19.0
	Tse-pear		89	3.9	53.9	
16 May 03	Ya-pear	29	115	10.2	53.0	19.9
	Tse-pear		101	8.5	81.2	
30 May 03	Ya-pear	31	130	8.7	86.2	21.4

[a] The assessment was done 3–7 days after the first lesion was seen

[b] Mean temperature outside the poly-tunnel from inoculation to the assessment date

May probably led to the first wave of lesions observed in early June (Fig. 2D). The subsequent increases (on 20 June and 12 July) can be associated with two severe infection periods forecast on 25 May and 16 June (Fig. 2D), respectively.

Zhao-Yuan

In 2004, the first infection was forecast on 26 April with an estimated 50% of conidia that had infected leaves; however, this infection apparently did not result in visible lesions (Fig. 3A). Early visible lesions observed on 20 June may have resulted from the two forecasted infection periods during late May. The sharp increase in number of lesions from 14 July was likely due to the severe infection period forecast on 16 June (Fig. 3A). In 2005, among the six forecast infection periods only two (5 May and 26 June) were severe (Fig. 3B). Early lesions were likely to have resulted from the infection forecast on 5 May whereas the late increase in lesions from 20 July probably resulted from infections forecast on 21 and 26 June (Fig. 3B).

Rou-Gu

In 2002, weather data were only available from 1 June. Four infection periods were forecast from 8

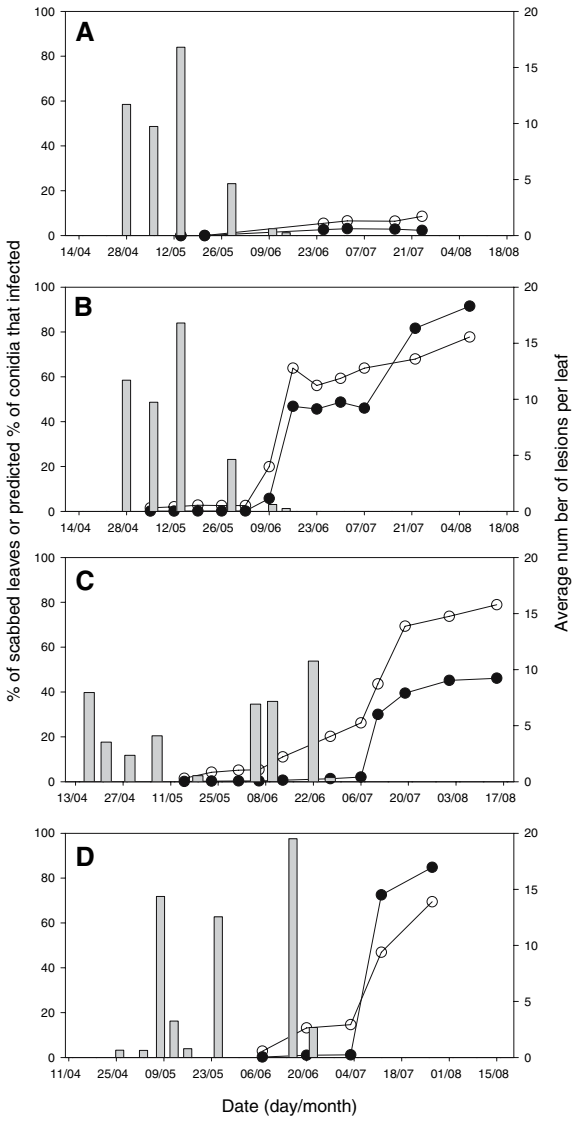

Fig. 2 Predicted leaf infection periods by *Venturia nashicola* (bars) and observed pear scab in the Xian Park orchard (**A** 2002) and the orchard near the Lai-Yang Agricultural College [(**B**) 2002; (**C**) 2003; (**D**) 2004]. Lines with unfilled and filled circles are % scabbed leaves and average number of lesions per leaf, respectively, on each assessment date

June to 26 June and these can be associated with the observed disease increase (Fig. 4A). In 2003, the overall level of disease level was low (Fig. 4B). Seven infection periods were forecast and they could explain the observed disease pattern. In 2004, there were eight infection periods forecast but % scabbed leaves remained at a very low level (<3%) during the entire season (Fig. 4C).

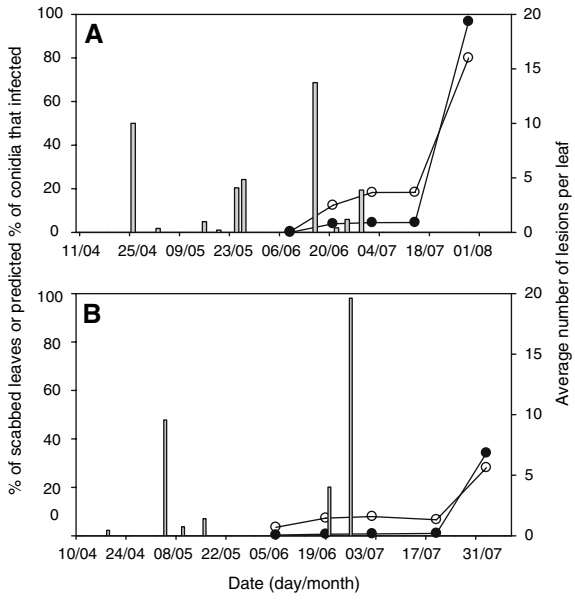

Fig. 3 Predicted leaf infection periods by *Venturia nashicola* (bars) and observed pear scab for the orchard in Zhao-Yuan [(**A**) 2004; (**B**) 2005]. Lines with unfilled and filled circles are % scabbed leaves and average number of lesions per leaf, respectively, on each assessment date

Discussion

This is a first attempt to develop a dynamic model to forecast infection of pear leaves by conidia of *V. nashicola*. It was mainly developed from laboratory and glasshouse experimental results on infection of pear seedlings (Li et al. 2005). It only considered the effects of weather variables on conidial development during the initial infection phase. Before the model is taken forward to large orchard trials to evaluate/demonstrate its usefulness in helping growers make decisions on disease control and how it can best be integrated with other farming practices, we need to determine whether the model can identify all important potential infection periods that may lead to outbreaks of disease symptoms. Present field studies suggest that this model is able to identify such potential infection periods.

Traditional approaches of disease management based on routine scheduled application of fungicides are being gradually replaced by a decision-based approach where the timing of fungicide applications partially depends on disease risks estimated from weather conditions and other information. These risks are usually estimated from mathematical models that

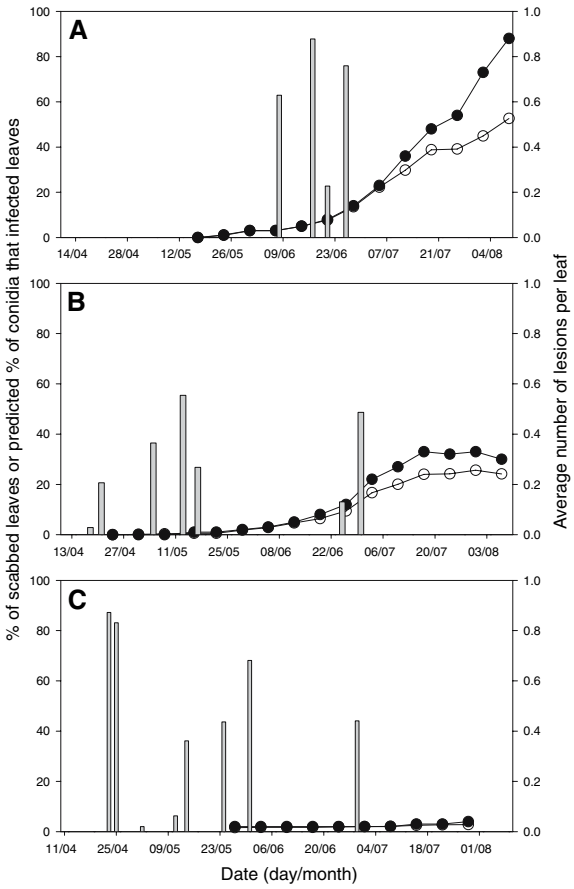

Fig. 4 Predicted leaf infection periods by *Venturia nashicola* (bars) and observed pear scab for the orchard in Rou-Gu [(**A**) 2002; (**B**) 2003; (**C**) 2004]. Lines with unfilled and filled circles are % scabbed leaves and average number of lesions per leaf, respectively, on each assessment date

identify when weather conditions are favourable for one or more stages of the pathogen's life cycle. As most of these models rely on time–wetness–temperature–disease relationships, growers must work within a constraint of relatively short response time once predicted risks are over an action threshold. The simplest disease forecasting model is a lookup table giving the risk of disease development in relation to important weather factors. One of most famous ones is the Mills table for apple scab (Mills 1944; Mills and La Plante 1954), which gives the risk of scab infection of leaves in three categories (light, moderate and severe) under various combinations of temperature and duration of wetness. Various versions of this simple model have been developed for different regions (e.g., Jones et al. 1980; MacHardy and Gadoury 1989). A more sophisticated dynamic simulation model was shown to be more reliable in identifying potential infection periods (Xu et al. 1995). Field evaluation demonstrated that this simulation model can be effectively integrated with commercial farming activities and lead to overall reductions in fungicide use while maintaining effective disease control (Berrie and Xu 2003).

Similar to the apple scab model (Xu et al. 1995), the present model simulates the infection process on susceptible leaves by conidia and is developed from the same rationale (the inter-relationships between duration of wetness, temperature during the wet period, and disease development). Indeed, this is a standard approach for developing disease forecasting models to assist in making tactical decision in disease management (Bulgar 1986; Gilles et al. 2001; Erincik et al. 2003). However, there are clear differences between the apple and pear scab models. As there are more extensive published data available on apple scab, the apple scab simulation model is more complex. For example, the infection process is divided into three sub-processes (germination, penetration and post-penetration); different mortality rates for conidia during the dry period are assumed for conidia in different sub-processes. In contrast, there is no such division of the infection process for pear scab. On the other hand, the pear scab model also considers conidial mortality due to extreme temperatures even during a wet period; conidial mortality is only considered during a dry period in the apple scab model.

Over the 4-year evaluation in unsprayed orchards, the model has identified all important infection periods that led to subsequent increases in the numbers of visible lesions on pear leaves, and particularly successfully for the orchards in Shandong Province. Overall, the increase in the incidence of infected leaves was much lower in the early season than in the late season irrespective of the number and severity of potential infection periods forecast by the model. This is likely to be due to the difference in the amount of inoculum at the time of infection. The present model only estimates the favourability of weather conditions for infection of pear leaves by conidia; thus it does not attempt to model or estimate total viable inoculum in orchards. For this reason, the model assumes that there is always a population of viable inoculum at the start of every potential

infection period, i.e., assuming that each infection period is initiated with 100% viable conidia without considering the absolute amount of inoculum. Early infections were initiated by overwintered inocula, which were usually very low. By contrast, infections during the late season are likely to be due to new conidia produced from primary infections. The amount of secondary inoculum is therefore expected to be greater than the overwintering inoculum in an unsprayed orchard. Thus, forecast infections by the model should be interpreted with the amount of inoculum present in orchards as well as cultivar susceptibility. In 2004, there were very few lesions in the Rou-Gu orchard even though several severe infection periods were predicted by the model. The main reason for this could be low survival of overwintering inoculum.

Conidia were considered as the main source of inoculum in primary and secondary infections in most areas of north China (Li 1959; Yin and Yu 1988). However, recently we have observed abundant productions of sexual structures of *V. nashicola* on pear leaves during the autumn (Lian et al. 2006). Currently, experiments are being conducted to investigate viability of ascospores in the spring and their potential role as primary inoculum. If ascospores are shown to play a key role in primary infections, we may need to incorporate ascospore infection into the model. This is essential because infection requirements may differ between conidia and ascospores as shown for apple scab (MacHardy 1996). Furthermore, spore release mechanisms may differ between conidia and ascospores. In apple scab, ascospore discharge is light-dependent; more spores are discharged during daylight hours than during the night (MacHardy and Gadoury 1986).

In apple scab, one of the key criteria for determining the timing of first spray in northern America is the estimated potential ascospore doses (Gadoury and MacHardy 1986; Gadoury et al. 1992; MacHardy 2000; Gadoury et al. 2004). Furthermore, prediction of ascospore maturity in the spring may also be important for better timing fungicide applications. Ascospore maturation models, usually based on degree-days, have been developed for apple scab (Gadoury and MacHardy 1982; Schwabe et al. 1989; Gadoury et al. 1992; Gadoury et al. 2004) and European pear scab (Spotts and Cervantes 1994; Spotts et al. 2000). In addition, the importance of overwintering conidia in apple scab as a primary inoculum has also received considerable attention (Becker et al. 1992; Moosherr and Kennel 1995; Holb et al. 2004; Holb et al. 2005a). In contrast, the effects of weather conditions on overwintering of *V. nashicola* inoculum, whether it is as conidia or ascospores, have not been adequately studied so far and further research is needed in this area.

One of the inherent limitations in evaluating model predictions against observed disease development under field conditions is the inability to associate each predicted infection event/period to observed lesions; this is particularly true when several predicted infection periods are clustered closely together. However, in practice, the close clustering of several infection periods is not an important issue because of the nature of scab control by fungicides. Usually, once fungicides are applied, plant tissues are protected from infection for a period of 7–14 days depending on weather conditions and the rate of plant growth as well as the efficacy of the fungicides. Thus, these clustered infection periods can be effectively treated as one.

It is almost inevitable that the model will over-forecast, i.e., generate too many false-positives as shown in this study. As discussed above, this over-forecasting is because the model does not incorporate the amount of viable inoculum and cultivar susceptibility. The model was derived from several laboratory studies on highly susceptible cultivars inoculated with a high inoculum concentration (Li et al. 2003, 2005). Thus, the forecasts from this model are always for the worst scenario. For use of this type of weather-based-only models, it is critically important that each predicted infection period should always be interpreted (or adjusted) using field assessment of inoculum and cultivar susceptibility. The inoculum assessment is particularly important during the secondary spread period because it can be assessed accurately. However, because of the difficulty in assessing overwintering inoculum, it would be advisable to assume the presence of primary inoculum. Otherwise, following the forecast infection periods without due considerations of other factors such as inoculum and tissue susceptibility may sometimes result in as much fungicide input as in a scheduled application programme. Nevertheless, even this approach would not normally lead to more fungicide input than a scheduled programme because

a scheduled programme is usually based on the length of protection periods given by fungicides, which does not differ between the two approaches. For the same reason, model forecasts should also be interpreted taking into account timing, the rate and volume of the last fungicide application and loss of fungicides due to rain wash-off, in addition to inoculum and cultivar susceptibility. This is essentially the principle by which the apple scab model assists in decision making on a commercial scale (Berrie and Xu 2003).

Pear scab has two peaks in northern China (Li 1959; Yin and Yu 1988). The first peak occurs during the early season and lasts about 2–3 months after blossom. At that time, pear leaves and fruit are young and very susceptible to infection; environmental conditions are often conducive to infection. The second peak occurs before harvest. Under favourable weather conditions, early infections not only result in a significant amount of fruit infection but also generate secondary inoculum for later infection. Thus, control of early infection is the key to successful management of pear scab in northern China. Orchard evaluation results suggested that the model can assist farmers in controlling early infections by correctly identifying potential infection periods. Based on the predicted infections, a maximum of four applications of fungicides are sufficient to manage the disease. As discussed above, current disease level and cultivar susceptibility should be assessed and incorporated in order to make decisions on the necessity of applying fungicides.

Over the 4-year evaluation period, all of the significant disease increases can be associated with infection periods predicted by the model. It is essential that further large field trials are carried out to evaluate whether use of this model in practice could lead to reduced input of fungicides whilst satisfactorily maintaining disease control. If so, we need to develop strategies that can effectively incorporate this model with other orchard management activities. Above all, farmers need to be convinced that a scientifically sound model can be relatively easily integrated with their management activities, and that use of such a model can lead to an overall reduction in fungicide use without compromising disease control.

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