A-scab (Apple-scab), a simulation model for estimating risk of *Venturia inaequalis* primary infections*

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A-scab (Apple-scab) is a dynamic simulation model for *Venturia inaequalis* primary infections on apple. It simulates development of pseudothecia, ascospore maturation, discharge, deposition and infection during the season based on hourly data of air temperature, rainfall, relative humidity and leaf wetness. A-scab produces a risk index for each infection period and forecasts the probable periods of symptoms appearance. The model was validated under different epidemiological conditions: its outputs were successfully compared with daily spore counts and actual onset and severity of the disease under orchard conditions, and neither corrections nor calibrations have been necessary to adapt the model to different apple-growing areas. Compared to other existing models, A-scab: (i) combines information from literature and data acquired from specific experiments; (ii) is completely 'open' because both model structure and algorithms have been published and are easily accessible; (iii) is not written with a specific computer language but it works on simple-to-use electronic sheets. For these reasons the model can be easily implemented in the computerized systems used by warning services.

Introduction

Apple scab, caused by *Venturia inaequalis* (Cooke) Wint., is the most important fungal disease of apple worldwide. It causes repeated infections on leaves and fruits during the season and it can cause severe yield losses when fungicides are not applied efficiently. Strategies for applying fungicides have changed greatly in recent decades, from spraying to a calendar to having a rational schedule based on actual infection risk. A key step in the development of rational fungicide use against apple scab was the Mills Table (Mills, 1944), which determines the minimum conditions of temperature and leaf wetness required for infection to occur, and works by relating ascospore maturation to weather conditions (Massie & Szkolnik, 1974; Gadoury & MacHardy, 1982; Schwabe *et al.*, 1989; Lagarde, 1988; St-Arnaud *et al.*, 1985).

Simulation models have been developed starting from these foundations. The first attempts in building models for apple scab date back to the 1970s. They were written with computer languages that are now obsolete and are not supported by validation processes, so that they now only represent interesting exercises of modelling biological processes (EPIVEN by Kranz *et al.* [1973]; Analytis [1973]; VISIM by Jones [1978]; APPLESCAB by Arneson *et al.* [1979]; the Minogue [1978] simulator).

A second generation of models was created in the 1980–90s. These models were elaborated to be run on a PC or were exclusively associated to meteorological stations. In several cases, information on the model structure and algorithms was lacking and only descriptions of model outputs were provided. Usually these models represent elaborations of data from literature, particularly from the works of Mills, Schwabe and MacHardy. Examples are: Seem simulator by Seem *et al.* (1989); Biomat by Hofmaier (1994); METY by Boshuizen & Verheyden (1994) which was implemented in the meteorological stations of Bodata Co. Ltd, Dortrecht, the Netherlands.

The models named VENTEM, elaborated by Santen & Butt (1992) in East Malling (GB), and RIMpro, elaborated by Trapman (1993) in the Netherlands, represent an important advance in modelling apple scab.

VENTEM was described in detail by Xu & Butt (1993) and it is mainly based on elaboration of data from literature. VENTEM was subsequently updated (versions 3.1 and 4.0) and afterwards it was included in ADEM (Berrie & Xu, 2003), together with other apple diseases, and then in MORPH (Methods Of Research Practice in Horticulture) which is a support system for English growers. According to literature reports it has never been validated in Italian orchards.

RIMpro was elaborated in the early 1990s, written in Visual Basic, and receved several improvements and updates. Although its theoretical bases were described in technical literature, its algorithms are not known. The model starts at the green tip stage and, based on meteorological data, determines pseudothecia development, ascospore maturation, ascospore

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releases and infection events, providing a severity estimation of each infection based on an arbitrary numerical scale called RIM (Relative Infection Measure). RIM values < 100 indicate weak infections; values > 300 indicate very severe infections. Results are represented both by table and graphs with time steps of one day or one hour. RIMpro was widely validated in Europe (Trapman & Polfliet, 1997); also providing good results, after suitable calibrations, in Italy (Mattedi & Varner, 2000; Spanna *et al*., 2002). RIMpro is a widely used model: it is now used by fruit growers in Europe and by advisory systems in Germany, Austria, the Netherlands, England and Italy (Trentino Alto Adige, Pordenone district). It is a commercial model and its use is possible by acquiring a licence from Bio Fruit Advies (Zoelmond, the Netherlands). It runs on a PC and users must perform simulations for each orchard or homogeneous area. Users cannot interact with the program but only change some parameters to adjust simulations to local conditions. This kind of use makes RIMpro inflexible for the needs of advisory systems working on a territorial scale.

For this reason a new simulation model was elaborated, including all the stages of the infection cycle based on the principles of 'systems analysis' (Leffelaar, 1993). A-scab (acronym of Apple Scab) is different from the previously described models for three main reasons: (1) it combines information from literature and data acquired from specific experiments; (2) it is completely 'open' because both model structure and algorithms have been published and are easily accessible; (3) it is not written in a specific computer language but works on simple-to-use electronic data sheets.

In this paper, the model structure and algorithms are described, while details about methods used to define the different algorithms, comparison with results found by other workers and validations have been described in previous publications.

Model description

The A-Scab model was elaborated following the principles of 'systems analysis' (Leffelaar, 1993). Its conceptual structure is shown in Fig. 1; the flow diagram in Fig. 2 shows the main steps of the model. A list of variables used in the model is shown in Table 1.

The model starts from the overwintering pseudothecia in above-ground leaf litter in the orchard. These pseudothecia develop and ascospores mature progressively during the primary inoculum season. Mature ascospores are repeatedly discharged from pseudothecia under favourable conditions, become air-borne and some portion of them land on apple trees. Ascospores on the surface of susceptible host tissue cause infection depending on weather conditions. Finally, infection sites become visible as scab symptoms at the end of incubation (Fig. 1).

Ontogenesis of pseudothecia

The first step of the model simulates ontogenesis of pseudothecia to determine the beginning of the primary inoculum season (Giosuè *et al*., 2000). Stages of pseudothecial development (st) are defined following James & Sutton (1982a), from st 5 (undifferentiated) to st 12 (ascospores pigmented and mature). Starting from February 1 (when all the pseudothecia are in st 5), the development of pseudothecia (Δst) on each ith day is calculated as a function of temperature (T), relative humidity (RH), rainfall (R), and wetness duration (WD) according to the model of James & Sutton (1982b) modified by Mancini *et al*. (1984):

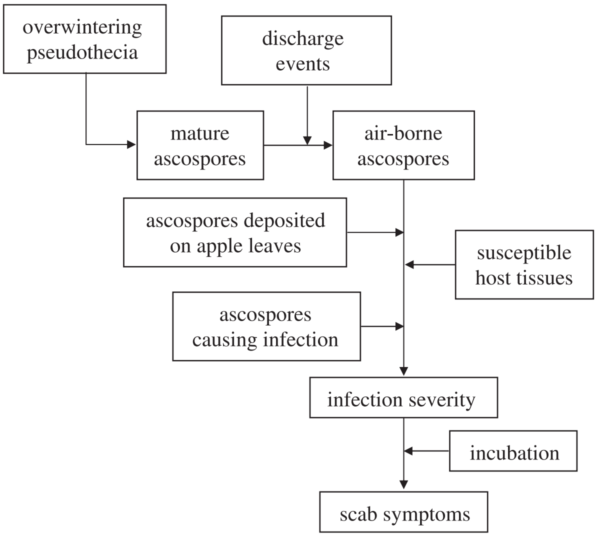

Fig. 1 Conceptual structure of the A-scab model simulating primary infections of *Venturia inaequalis*.

$$\Delta st_i = 0.0031 + 0.0546 \cdot T_i - 0.00175 \cdot T_i^2 \quad [1]$$

$$\text{if } T_i \le 0\ °C\text{, then } \Delta st_i = 0 \quad [2]$$

$$\text{if } R_i \le 0.25 \text{ mm or } RH_i > 85\% \text{ for less than 8 h or } WD_i < 8 \text{ h, then } \Delta st_i = 0 \quad [3]$$

Equations [1] and [2] describe the influence of T on pseudothecial development when leaf litter moisture is not a limiting factor, while equation [3] accounts for the limiting effect of dryness on pseudothecial development.

The development stage of pseudothecia on the current day j is then calculated as:

$$st_j = 5 + \sum_{i=1}^{j} \Delta st_i \quad [4]$$

where: i = counter of the days from February 1 (i = 1) to the current day j; 5 = st 5.

The model considers that first mature ascospores are present when $st_j \ge 9.5$, which corresponds to the time when 2% of pseudothecia contain pigmented and mature ascospores. This threshold was determined by considering the data of James & Sutton (1982a) concerning variability within the overwintering population in reaching an ontogenic stage

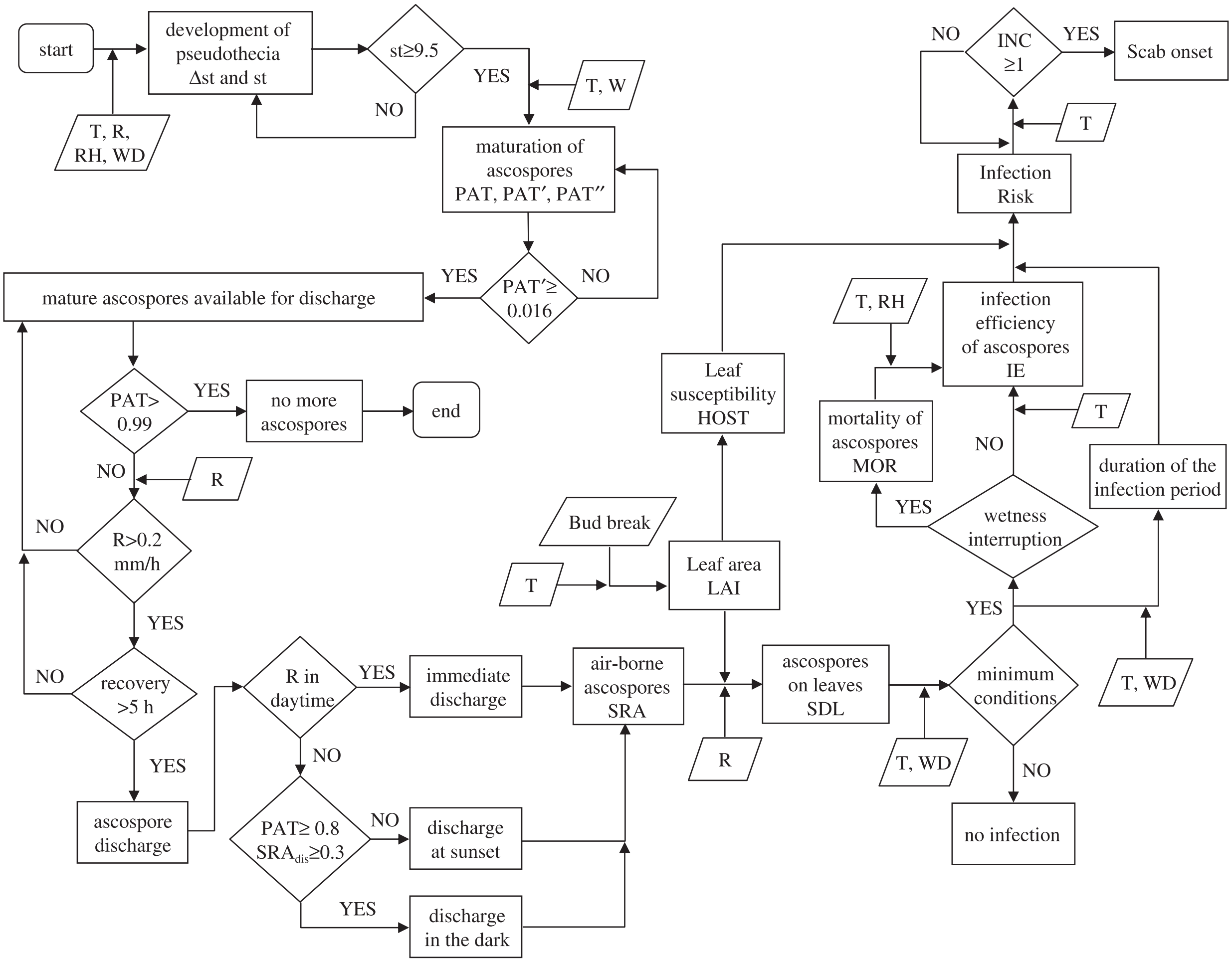

Fig. 2 Flow-diagram of the main steps of the A-scab model (see Table 1 for explanations of variables).

(Giosuè *et al*., 2000). This time is considered as the biofix (or starting point) for calculating the dynamics of ascospore maturity over time.

The inoculum dose at the beginning of the primary season is set to one. It corresponds to the potential ascospore dose usually present in commercial orchards well managed against apple scab in the previous seasons. It is possible to increase or decrease this initial setting when precise information is available about potential ascospore dose (Gadoury & MacHardy, 1986).

Maturation of ascospores

The dynamic of ascospore maturation is calculated indirectly, by determining the proportion of seasonal ascospores that can potentially become airborne on each ith day (PAT). The model uses three equations to define PAT and its 99% confidence bands (Rossi *et al*., 2000):

$$PAT_i = 1/(1 + e^{(6.89-0.035 \cdot DHW_i)}) \qquad [5]$$

$$PAT_i' = 1/(1 + e^{(5.41-0.035 \cdot DHW_i)}) \qquad [6]$$

$$PAT_i'' = 1/(1 + e^{(8.27-0.035 \cdot DHW_i)}) \qquad [7]$$

where:

$$DHW_i = \sum_{h=1}^{24} T_h \cdot W_h \qquad [8]$$

where: T_h is temperature in each h hour (h = 1–24) of the i^{th} day (if $T_h < 0$, $T_h = 0$); W_h defines the presence of wetness on each h, with W = 1 (presence of wetness) or W = 0 (no wetness).

These equations have been previously elaborated by Rossi *et al.* (2000) because neither the New Hampshire model for ascospore maturation (Gadoury & MacHardy, 1982) nor modifications introduced by Stensvand *et al.* (2005) to account for the effect of dryness in lengthening maturation satisfactorily fitted the dynamics of airborne ascospores in the Po Valley, Italy (Rossi *et al*., 1999). This model was elaborated using records from a volumetric spore sampler as the independent variable. For this reason the values of PAT include the effects of leaf litter decomposition or of environmental stresses that affect ascospore maturation (MacHardy, 1996).

Table 1 Acronyms, description, units and reference number to equations containing the variables included in the A-scab model

Acronym	Description	Unit	Equation
ΔINC	Daily progress of incubation	0–1	[25]
Δst	Daily pseudothecial development	1–12	[1]
d	Distance from the inoculum source	m	
DHW	Degree hours (base 0°C) when W = 1	°C	[8]
h	Counter for the hours	–	
H1	Height above the ground of the lowest leaves	m	
HOST$_{inf}$	Index of host susceptibility	arbitrary scale	
i	Counter of the days from February 1	–	
IE$_{inf}$	Infection efficiency of ascospores	0–1	
j	Current day	–	
LAI	Leaf area index	m^2 leaf/m^2 soil	
LDR	Apple leaf development rate	0–1	[23]
MOR	Mortality rate of ascospores	0–1	[20], [21], [22]
n	number of days	–	
PAT	Proportion of ascospores that can become airborne	0–1	[5]
PAT′, PAT″	99% confidence bands of PAT	0–1	[6], [7]
R	Rainfall	mm	
RH	Relative humidity	%	
RH$_{dry}$	Average RH during interruption of a wet period	%	
Risk$_{inf}$	Risk of scab infection	arbitrary scale	[24]
S1	Non germinated ascospores	0–1	[12]
S2	Germinated ascopsores	0–1	[16], [17]
S3	Ascospores with appressorium	0–1	[18], [19]
SDL$_{dry}$	Part of SDL$_h$ deposited by dry deposition	0–1	[15]
SDL$_h$	Proportion of ascospores deposited on apple leaves	0–1	[12]
SDL$_{wet}$	Part of SDL$_h$ deposited by wet deposition	0–1	[13], [14]
SRA$_{dis}$	Part of PAT becoming airborne on a discharge event	0–1	[9]
SRA$_h$	Distribution of SRA$_{dis}$ over hours of H$_{dis}$	0–1	[11]
st	Stage of pseudothecial development	1–12	[4]
T	Air temperature	°C	
t$_{dis}$	Duration of a discharge event	hours	[10]
T$_{dis}$	Average T during a discharge event	°C	
t$_{dry}$	Duration of interruption of a wet period	hours	
T$_{dry}$	Average T during interruption of a wet period	°C	
t$_{inf}$	Hours of wetness of an infection period	hours	
T$_{inf}$	Average T of an infection period	°C	
U	Wind speed	m/s	
W	Hour with wetness: 1 = yes, 0 = no	0/1	
WD	Wetness duration	hours/day	

Based on equations [4] to [7] the model defines different levels of risk for the presence of inoculum (Giosuè *et al.*, 2000; Rossi *et al.*, 2001a): $st < 9.5$, no risk (pseudothecia do not contain mature ascospores); $PAT' \geq 0.016$, beginning of risk (first ascospores are ready to be discharged); $PAT' = 0.5$ to $PAT'' = 0.5$, maximum risk (most of the seasonal ascospores are mature and ready to be discharged); $PAT \geq 0.99$, risk finished (all ascospores have been ejected and the risk of scab primary infections is finished).

Ascospore discharge events

The model considers that mature ascospores become airborne when weather conditions favour ascospore discharge from pseudothecia. The model defines: (i) events of ascospore discharge (ii) time of the day when such a discharge occurs (iii) its duration, and (iv) the corresponding proportion of seasonal ascospores becoming airborne.

Weather conditions for ascospore discharge have been defined using data from spore traps (Rossi *et al.*, 2001b). A 'rain event', i.e. a period with measurable rainfall ($R \geq 0.2$ mm/h) lasting one to several hours, interrupted by maximum of two hours, is the only occurrence allowing ascospores to become airborne; dew does not allow spore dispersal at a measurable rate in the absence of rain. After PAT′ has reached 0.016, daytime rain events cause the instantaneous discharge of mature ascospores so that they begin to be airborne immediately. For night-time rainfalls there is a delay, so that ascospores became airborne at sunset. This delay does not occur, and consequently ascospore are discharged in the dark, when:

(i) $PAT \geq 0.80$
(ii) more than one third of the total season's ascospores is mature inside pseudothecia ($SRA_{dis} \geq 0.30$, where SRA_{dis} is the part of PAT becoming airborne on the discharge event).

A rain event does not lead to spore ejection when:
(i) it occurs after less than 5 h from the preceding discharge event
(ii) leaf litter dries before 7.00 am following a rain event in night time when $PAT < 0.80$
(iii) nightly rainfalls are followed by heavy dew deposition that persists some hours after sunrise (Rossi *et al.*, 2001b).

The ascospore dose ejected during a discharge event is calculated as:

$$SRA_{dis} = PAT_i - PAT_{i-n} \qquad [9]$$

where: SRA_{dis} = proportion of ascospores released into the air during the discharge event; PAT_i = value of PAT on the day when ascospores are discharged; PAT_{i-n} = value of PAT on the day $i - n$, where n is the number of days elapsed from the preceding discharge event.

The model considers that the total ascospores released on a discharge event become airborne over the next hours. This displacement influences their probability of causing infection because ascospores released at the beginning of a discharge period may encounter different environmental conditions compared to those released at the end of the same period (MacHardy, 1996). The model uses equations [10] and [11] to distribute SRA_{dis} over time with a time step of one hour (Rossi *et al.*, 2003a), so that the further steps of the infection chain will be calculated hourly.

Equation [10] defines duration (in hours) of a discharge event (t_{dis}), as follows

$$t_{dis} = 90.96 \cdot T_{dis}^{-0.96} \qquad [10]$$

where: T_{dis} = average temperature during the discharge event.

Equation [11] distributes the ascospore dose ejected on each SRA_{dis} over hours of t_{dis}, as follows

$$SRA_h = 1/[1 + \exp(2.999 - 0.067 \cdot T_{dis} \cdot h)] \qquad [11]$$

where: h = hours from the beginning of the discharge event (h = 1) to t_{dis}.

Ascospore deposition

Once ascospores are released in the orchard air, deposition on apple leaves is calculated by means of equations elaborated from a complex mechanistic model describing ascospore deposition (Rossi *et al.*, 2003b; Rossi *et al.*, 2006a). Ascospores are removed from the air and deposited on plants and on the ground by a combination of wet and dry deposition processes, depending on the available host surface (expressed as LAI, Leaf Area Index), R, wind speed (U) and distance from the inoculum source (d). The last parameter was set at zero because inoculum has a random distribution on the ground under the apple canopy, while U was not considered because wind speed does not significantly affect deposition when d = 0 (Rossi *et al.*, 2006a).

The proportion of airborne ascopores that deposit on leaves per hour is calculated as a sum of wet and dry deposition, as follows:

$$SDL_h = SDL_h(\text{wet}) + SDL_h(\text{dry}) \qquad [12]$$

where:

$$SDL_h(\text{wet}) = (1.017 \cdot 0.374^{H1}) \cdot \lambda_h \qquad [13]$$

$$\lambda_h = 1/\{1 + \exp[2.575 - 0.987 \cdot LAI \cdot (5.022 \cdot R_h^{0.063})]\} \qquad [14]$$

$$SDL_h(\text{dry}) = 0.594 - (0.643 \cdot 0.372^{LAI}) \qquad [15]$$

where: H1 = height above the ground of the lowest leaves of the apple trees; LAI = Leaf Area Index of the apple trees (in m^2 leaf/m^2 soil).

Equation [13] accounts for the proportion of SRA_{dis} that remain in the air layer between the ground and the lowest leaves: these spores do not reach the apple canopy and must be removed from SRA_{dis}. Equation [14] accounts for the proportion of such an ascospore dose that lands on the apple leaf surface, as a function of LAI and R. Equation [15] accounts for ascospores that are contained in the air but not in rain drops, which are deposited by gravitational settling (or sedimentation) and by inertial impaction.

Infection

The model calculates infection efficiency of the ascospores deposited on the apple leaves with a time step of one hour. As a first step, the model verifies the possibility for ascospores to cause infection. At any discharge event, the model defines conditions for a potential infection period, as hours of wetness (t_{inf}) and correspondent average temperature (T_{inf}). An infection event is composed by two wet periods interrupted by a dry period of at least 4 h; shorter interruptions of the wet period are not considered as interruptions. For instance, the following situation: 8 h wet +2 h dry +6 h wet +8 h dry +12 h wet, represents a potential infection period with t_{inf} = 26 h and a T_{inf} calculated by averaging T during wetness, disregarding interruptions. t_{inf} and T_{inf} are compared with the table of Stensvand *et al.* (1997) which defines minimum conditions for infection of apple leaves by ascopores to occur. Based on this comparison, the potential infection event is considered or not.

Infection efficiency of ascospores is determined considering that the deposited ascospores go through the following development stages: nongerminated ascospores (S1), germinated ascospores (S2) and ascospores with appressorium (S3). Ascospores in S1 correspond to the variable SDL_h and those in S2 and S3 are calculated as a function of time (t_{inf}) and temperature (T_{inf}) using the following equations developed combining data from Turner *et al.* (1986) and Boric (1985) (Rossi *et al.*, 2006b):

for $T_{inf} \leq 20°C$

$$S2_h = 1/(1 + \exp((5.23 - 0.1226 \cdot T_{inf} + 0.0014 \cdot T_{inf}^2) - (0.093 + 0.0112 \cdot T_{inf} - 0.000122 \cdot T_{inf}^2) \cdot t_{inf})) \quad [16]$$

for $T_{inf} > 20°C$

$$S2_h = 1/(1 + \exp((-2.97 + 0.4297 \cdot T_{inf} - 0.0061 \cdot T_{inf}^2) - (0.416 - 0.0031 \cdot T_{inf} - 0.000245 \cdot T_{inf}^2) \cdot t_{inf})) \quad [17]$$

for $T_{inf} \leq 20°C$

$$S3_h = 1/(1 + \exp((6.33 - 0.0647 \cdot T_{inf} - 0.000317 \cdot T_{inf}^2) - (0.111 + 0.0124 \cdot T_{inf} - 0.000181 \cdot T_{inf}^2) \cdot t_{inf})) \quad [18]$$

for $T_{inf} > 20°C$

$$S3_h = 1/(1 + \exp((-2.13 + 0.5302 \cdot T_{inf} - 0.00913 \cdot T_{inf}^2) - (0.405 + 0.0008 \cdot T_{inf} - 0.000347 \cdot T_{inf}^2) \cdot t_{inf})) \quad [19]$$

Ascospores in each stage are calculated for each hour by simply subtracting the spores moved to the successive stage. In the case of interruption of the wet period, the mortality rate of spores (MOR) is calculated for each development stage (S1 to S3) based on the duration of interruption (t_{dry}) and the correspondent values of T (T_{dry}) and RH (RH_{dry}), using the following equations:

$$MOR1_h = 0.263 \cdot (1 - 0.97315^{t_{dry}}) \quad [20]$$

$$MOR2_h = (-1.538 + 0.253 \cdot T_{dry} - 0.00694 \cdot T_{dry}^2) \cdot (1 - 0.977^{t_{dry}}) \cdot (0.0108 \cdot RH_{dry} - 0.08) \quad [21]$$

$$MOR3_h = (0.0028 \cdot t_{dry}) \cdot (-1.27 + 0.326 \cdot T_{dry} - 0.0102 \cdot T_{dry}^2) \quad [22]$$

where: MOR1, MOR2, MOR3 = mortality rate of ascospores in each stage; h = counter for the hours from the first hour of interruption to t_{dry}.

To calculate the ascospores that had survived the period of dryness, values of S1, S2 and S3 at the beginning of the dry period are multiplied by 1-$MOR1_h$, 1-$MOR2_h$ and 1-$MOR3_h$, respectively. The value of S3 at the end of the infection period is IE_{inf}, i.e. the proportion of ascospores that had caused infection during the infection period.

Host susceptibility

It is well known that apple leaves have different levels of susceptibility to scab infection depending on their age, the young leaves being more susceptible than the older ones (Aylor & Kiyomoto, 1993). The model considers that the severity of a scab infection depends on the amount of susceptible leaf tissue to be infected. A daily index of leaf development is calculated as follows. Starting from green tip of the apple trees, the daily increase of LAI is calculated by multiplying average T (base 4 °C) times 0.00008 (Lasko & Johnson, 1990), and these values are cumulated over the season to obtain LAI_i. The rate of leaf development (LDR) is then calculated on each day i as:

$$LDR_i = 1/(-5445.5 \cdot LAI_i^2 + 661.55 \cdot LAI_i) \quad [23]$$

The average of LDR between two successive infection periods is then calculated as an index of host susceptibility ($HOST_{inf}$).

Risk index

The risk index for each infection period is finally calculated as:

$$Risk_{inf} = \sum_{i=1}^{n} SRA_{dis} \cdot IE_{inf} \cdot HOST_{inf} \cdot 100 \quad [24]$$

where: n = number of days including the infection period.

Incubation

The model defines the possible period of scab symptom appearance for each infection event. It calculates the daily progress of incubation (ΔINC) on each day i as a function of T using the following equation:

$$\Delta INC_i = 1/(26.4 - 1.0286 \cdot T_i) \quad [25]$$

These values are cumulated starting from the beginning of an infection period and the incubation finishes when this summation is ≥ 1. At this time symptoms are expected to appear.

Model output

The model can produce different outputs, at both hourly and daily scales. Outputs to be used to advise technicians or growers change based on needs of the different warning services. For instance, in Basilicata, a very short information is sent to growers by SMS, concerning infection periods and severity. In Piedmont, more detailed information is provided to technicians on the web (http://www.sistemapiemonte.it/agricoltura/modelli_agrometeo/index.shtml) (Fig. 3).

Model validation

A-Scab is now in use for alerting technicians or growers in some apple-growing areas of Italy, about 11 500 ha wide. In all these cases the model has been validated before its practical use for a period of at least three years. Validations were performed by comparing model outputs with actual data concerning both air-borne ascospores, measured by spore traps, and disease onset assessed in representative orchards following specific protocols. Meteorological data used as model inputs were collected in the nearest automatic station of the regional networks.

Validations always produced correct simulations and neither corrections nor calibrations have been introduced for adapting the model to the different apple-growing areas. For instance, in 21 orchards considered in three different areas between 2002 and 2005, the model was accurate in simulating the dynamic of ascospore maturation because the most part of actual spore traps fell within the 99% confidence limits of PAT, and the simulated appearance of scab symptoms corresponded to the

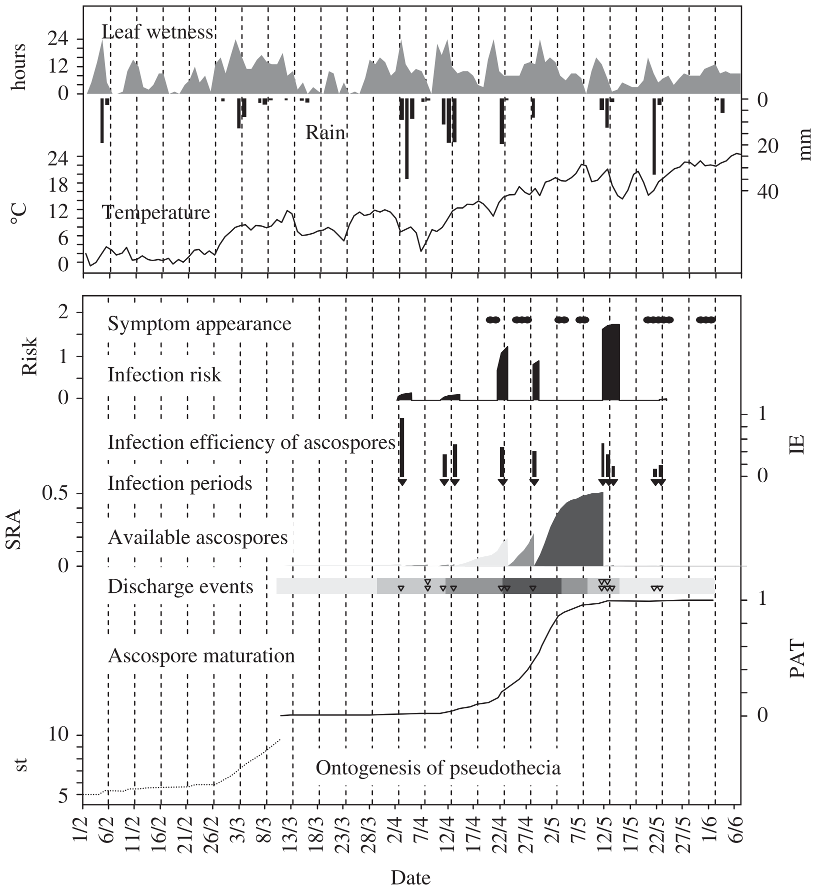

Fig. 3 Example of the outputs provided by the A-scab model (see Table 1 for explanations of variables).

Table 2 Comparison between first seasonal scab infection observed in 21 apple orchards (2002–05) and the corresponding warnings provided by A-scab

		Appearance of scab symptoms		
		Yes	No	Total
Scab warnings[a]	Yes	20 (39.2%)	8 (15.7%)	28 (54.9%)
	No	1 (2.0%)	22 (43.1%)	23 (45.1%)
	Total	21 (41.2%)	30 (58.8%)	51
	χ^2	20.771 ($P < 0.0001$)		

Values between brackets represent relative frequencies with respect to the total number of observations; χ^2 is the calculated value of the chi-square test using the Yates correction for a 2 × 2 contingency table and P is its significance level. [a]Scab warnings correspond to a simulated infection period with $\text{Risk}_{\text{inf}} \geq 0.2$.

actual disease onset in the orchard. Moreover, the dimension of the Risk index was strictly related to actual infection severity: high risk index values corresponded to severe infections in the orchard.

Table 2 shows a detail of these validations. In the period between bud break and first actual disease onset, the model simulated 51 infection periods: 23 of these periods had a level of risk too low for an infection warning (Risk < 0.2), while the other 28 periods were considered as true infection periods. These simulations were correct in 42 cases (82.3%). In 8 cases (16%) A-scab provided a warning but scab symptoms were not actually observed within the period of symptoms appearance simulated by the model (unjustified warnings), while in only one case the model did not signal an actual infection. It happened in an orchard located in Piedmont. A-scab forecasted the first infection period on 13–17 April 2004, with an estimated appearance of symptoms between 26 and 28 April, but first scab symptoms were observed on 6 May; therefore symptoms had appeared between 30 April (no disease observed) and 6 May. The chi-square test, calculated using the Yates correction for a 2 × 2 contingency table, was applied to the data of Table 2 to verify the null hypothesis of independence between simulated and actual infections. This test showed a significant association ($P < 0.0001$) between model simulations and actual data.

Conclusions

A-scab is a dynamic simulation model elaborated using the principles of the systems analysis. It follows step by step all the stages of *V. inaequalis* primary infection cycles. All the model algorithms are published and they work on simple electronic sheets. For this reason the model can be easily implemented in the computerized systems used by the different warning services. It is suggested to perform validations before introduction of A-scab in a new apple-growing area, even if in all the validations performed to date neither corrections nor calibrations have been necessary. The inoculum dose at the beginning of the primary season is dimensioned to commercial orchards well managed against apple scab, but it is possible to increase or decrease this initial setting.

The model provides different information useful for warnings about apple scab management, such as infection periods, their relative severity and time of possible appearance of symptoms. To date A-scab is included in the advisory systems of Emilia-Romagna, Piedmont and Basilicata, where it runs daily on all the stations of the regional meteorological networks.

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A-scab (Apple scab), un modèle de simulation pour estimer le risque d'infections primaires de *Venturia inaequalis*

A-scab est un modèle dynamique permettant de simuler les infections primaires de *Venturia inaequalis* sur pommier. Il simule le développement des pseudothèces, la maturation, la libération, et le dépôt des ascospores et l'infection au cours de la saison en se basant sur des données horaires pour la température de l'air, les précipitations, l'humidité relative et l'humectation foliaire. A-scab élabore un index de risque pour chaque période d'infection et prévoit les périodes probables d'apparition des symptômes. Le modèle a été validé dans différentes conditions épidémiologiques: ses résultats sont satisfaisants quand on les compare avec des comptages journaliers de spores, et à la date d'apparition et à la sévérité de la maladie dans les conditions réelles du verger ; aucune correction ou calibration n'a été nécessaire pour adapter le modèle aux différentes zones de production. Par rapport à d'autres modèles existants, A-scab: i) combine des informations de la littérature et des données acquises au cours d'expérimentations spécifiques; ii) est complètement 'ouvert' parce que la structure du modèle ainsi que les algorithmes ont été publiés et sont facilement accessibles; iii) n'est pas écrit avec un langage informatique spécifique et fonctionne selon des modalités d'utilisation simples. Pour ces raisons, le modèle peut facilement être mis en œuvre dans les systèmes informatiques utilisés par des services d'avertissements agricoles.

A-scab (Apple scab) – симулирующая модель для оценки риска первичного заражения *Venturia inaequalis*

A-scab представляет собой динамичную модель первичного заражения яблони *Venturia inaequalis*. Модель симулирует развитие псевдотеций, созревание аскоспор, выброс, отложение и заражение в течение сезона на основе почасовых данных по температуре воздуха, выпадению осадков, относительной влажности воздуха и влажности листьев. Модель A-scab выдает индекс риска для каждого периода заражения и предсказывает вероятные периоды появления симптомов. Модель прошла валидацию в различных эпидемиологических условиях: ее результаты прошли успешное сравнение с дневным подсчетом спор и действительным установлением заражения и серьезностью заболевания в условиях плодового сада, причем для ее адаптации к различным районам выращивания яблок никакой корректировки или калибровки этой модели не требовалась. По сравнению с другими существующими моделями A-scab: i) обобщает информацию из литературы и данные, полученные в ходе конкретных экспериментов; ii) является совершенно «открытой», т.к. как ее структура, так и ее алгоритмы уже были опубликованы и к ним имеется легкий доступ; iii) не написана на каком-либо специальном языке программирования, а работает с помощью простых электронных таблиц. В силу перечисленных выше причин модель может легко внедряться в компьютерные системы, используемые службами предупреждения.

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