Disease progression of peach powdery mildew in Catalonia, Spain – Towards a decision support system based on degree-days to initiate fungicide spray programs

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ABSTRACT

The incidence of peach powdery mildew (PPM) was monitored on fruits of untreated trees in order to: i) describe the disease progress in relation to accumulated degree-days (ADD) after 50% blossom, and ii) establish an ADD operating threshold to initiate a fungicide spray program. PPM incidence was monitored from spring to summer in 2013-15 in commercial orchards. Disease onset was observed at 242 ± 13 ADD and progressed following a sigmoid curve until being asymptotic after 484 ± 42 ADD. Beta-regression models between disease incidence and ADD were fitted using Bayesian inference. An operating threshold to initiate fungicide applications was established at 220 ADD, coinciding with an expected incidence between 0.02 and 0.05. A commercial validation was conducted in 2017 by comparing PPM incidence in: i) a standard, calendar-based program, ii) a program with applications initiated at 220 ADD, and iii) a non-treated control. A statistically relevant reduction in disease incidence was obtained with both fungicide programs, from 0.2440 mean incidence in the control to 0.0727 with the 220-ADD alert program and 0.0488 with the standard program. Although statistically relevant, differences between both fungicide programs were not substantial. The 220-ADD alert program resulted in 33% reduction in fungicide applications.

INTRODUCTION

The ascomycete *Podosphaera pannosa* (Wallr.) de Bary, causal agent of the powdery mildew of peach (PPM), is a cosmopolitan biotrophic pathogen that has been reported from over 40 peach-growing countries in the world (Amano 1986; Farr and Rossman 2019). It is also known to affect other Rosaceae species, mainly included in the genera *Prunus* and *Rosa* (Farr and Rossman 2019). On peach, including all fruit morphologies such as nectarines and flat fruits, the fungus infects fruits, leaves, buds, shoots and twigs (Grove 1995; Ogawa and English 1991), showing a distinguishable white-greyish mycelium developing on the surface of the affected parts. The pathogen overwinters as dormant mycelium in latent buds (Ogawa and English 1991; Weinhold 1961; Yarwood 1957), and in chasmothecia produced in the epiphytic mycelium of infected twigs and leaves (Butt 1978). Primary infections on the tree green parts occur in spring, when the primary inoculum, as ascospores, is available and favorable conditions are met. Infections from latent mycelium that overwintered in buds have also been reported (Weinhold 1961). Conidia released from these primary colonies disperse in air and initiate secondary infections throughout the season (Grove 1995; Jarvis et al. 2002). Infection of fruits, if severe, makes the fruit unacceptable to industry (Weinhold 1961), thus causing an important economic loss.

Data on potential yield reduction by PPM have been previously reported in some countries. In California, Ogawa and Charles (1956) reported that the amount of marketable peaches from fungicide-sprayed trees was about 20% greater than those from unsprayed trees. Grove (1995) reported that crop losses resulting from fruit infections may reach 50% on Japanese plums, apricots, nectarines and peaches. Unfortunately, no data on potential production losses are available in Spain, where this study has been carried out. Nevertheless, Spain ranks as the second country in the world, after China, in terms of cultivated area (86,000 ha) and annual fruit production of peaches (1,5 M tons in 2016), followed by Italy, USA and Greece (FAO 2019; MAPA 2019). These figures account for about 6% of the total world crop area and 7% of the world production.

The control of PPM is usually achieved through the applications of fungicides (Grove 1995; Hollomon and Wheeler 2002; Ogawa and English 1991). Most used fungicides are sterol biosynthesis inhibitors (SBI), quinone outside inhibitors (QoI), protein synthesis inhibitors, and various inorganic multi-site activity products including sulfur derivatives. Foliar applications of fungicides, starting at petals fall or the beginning of fruit set, are done routinely to protect peach fruits from infection (Grove 1995; Reuveni 2001), as fruits are susceptible from the early stages of fruit growth to about the beginning of pit hardening (Ogawa and English 1991). In Spain, four to seven applications in a season are generally needed, which is comparable to other Mediterranean countries where peaches are grown (Reuveni 2001). In California, it has been reported that three applications are enough to control the disease (Ogawa and Charles 1956; Ogawa and English 1991). However, fungicide applications are done on a calendar basis (Ogawa and English 1991) since, to our knowledge, no epidemiological models to predict the risk infection of PPM are currently available.

Disease prediction is required to apply plant protection products in rational, sustainable integrated strategies, which are intended to keep control effectiveness against plant diseases while reducing the application costs and the potential risks to the environment and public health (Jørgensen et al. 2017). Thus, optimizing timing of fungicide application is fully desirable for economic and environmental reasons (Jørgensen et al. 2017). Several epidemiological models have been developed for powdery mildews affecting different crops, including apple, barley, grape, rose, rubber, sugar beet and tomato, as reviewed by Jarvis et al. (2002), cherry (Grove et al. 2000) cucurbits (Sapak et al. 2017), mango (Nasir et al. 2014), and wheat (Cao et al. 2015). In general terms, models focus on the prediction of 1) the critical date for a single fungicide application, 2) the date to initiate the fungicide program, or 3) the timing of fungicide applications in intensive spray programs, as reviewed by Butt (1978).

Empirical (correlative) and mechanistic (process-based) modelling approaches have been used to develop decision support systems for plant disease management . Empirical models are correlative in nature, so their predictive ability is limited by the scope of the data (Madden and Ellis, 1988). Mechanistic models are developed from controlled experiments to quantify the effects of environmental factors on the different components of the disease cycle (De Wolf and Isard, 2007). Mechanistic models are generally considered robust for extrapolation, but epidemics are sometimes more complex than a simple combination of their monocyclic components.

This study aimed at acquiring new knowledge on the disease progress of PPM under the crop conditions in Catalonia, Northeast Spain, and to develop and validate a decision support system (DSS) adapted to this area. The specific objectives of this study were: *i*) to describe the disease progression of powdery mildew on peach and nectarine fruits in terms of incidence along the season, *ii*) to develop a simple epidemiological model to estimate the disease incidence in relation to temperature; and *iii*) to evaluate the performance of this empirical model as a DSS to initiate the fungicide spray program for PPM management.

MATERIALS AND METHODS

Experimental sites

The incidence of powdery mildew on peach and nectarine fruits was monitored yearly along the growth season in the period 2013-2015 in eight commercial orchards (1 to 8) located in Lleida, Catalonia, Spain and aged 4 to 8 years at the beginning of the experiment (Table 1). Most orchards were nectarine crops whereas only one was cultivated for peach, and an additional one for platerine. The commercial validation of the DSS (Magarey and Sutton, 2007) for the onset of fungicide applications was conducted in 2017 in six orchards, namely 2, 8 and four additional ones, 9 to 12 (Table 1). All orchards (1 to 12) were included within a radius of approximately 10 km. Trees in the orchards were drip-irrigated and trained in 4-scaffolds open vase, which is locally common in the area. The climate in the area is BSk (Tropical and Subtropical Steppe Climate), according to Köppen-Geiger’s climate classification system (Kottek et al. 2006).

Dynamics of powdery mildew symptoms on fruits

For each growing season and experimental plot, symptoms of PPM were recorded on fruit starting from the 50 % blossom biofix (mid-March) until no further disease progression was noticed for up to 2-3 weeks, which occurred in mid-June to early July depending on the year. Observations of PPM symptoms were carried out on a weekly basis but twice a week in some sites and seasons, especially when incidence progressed rapidly. The observations were conducted on five contiguous trees, which were not treated with fungicides during the growing season, thus allowing for a natural progress of disease. The trees were surrounded by 1-2 rows of non-treated trees to avoid any potential spray drift. In each tree, 3-4 scaffolds were selected and the central third of each branch was marked. All the fruits in the selected branch sections were recorded as either symptomatic or not and those showing symptoms were individually labelled. At the end of the monitoring period, all fruits in each monitored branch sections were counted and disease incidence was calculated as the proportion of symptomatic fruit (0 to1) for each monitoring period, branch, tree and experimental site combination. Any diseased fallen fruit during the monitoring period was considered as a diseased fruit to avoid underestimates of disease incidence (i.e., decrease) with time.

Meteorological data

A wireless cellular data-logger (model Em50G, from Decagon Services, Pullman, WA, USA) was located in each experimental site, less than 50 m away from the marked tress. The data-logger was used to measure the air temperature, relative humidity, rainfall and wetness duration at 1-hour intervals during the whole experimental period. Meteorological variables were summarized for each period between two consecutive symptom evaluations as follows: mean values of temperature and relative humidity, and accumulated values of rainfall and leaf wetness duration. In addition, degree-days (DD) were calculated according to Zalom et al. (1983), by using the single-sine method and setting the extreme values 10 °C and 35 °C as the lower and higher thresholds, respectively. Thresholds were determined from the values reported for *Podosphaera fuliginea*

(Jarvis et al. 2002). Finally, accumulated degree-days (ADD) for each monitoring date were calculated starting from the 50 % blooming biofix date.

Modelling of disease progression

Beta regression assumes that the response variable is within the interval (0,1) (Ferrari and Cribari-Neto 2004; Martínez-Minaya et al., 2019), although, in any interval (a,b) is possible, since it can be transformed easily to (0,1). As in generalized linear models (GLM), the mean (μ_i) is linked to the linear predictor using the logit link function:

$$logit(\mu_i)=\beta_0+\sum_{j=1}^{N_\beta}\beta_j x_{ji}+\sum_{k=1}^{N_f} f_k(z_{ki})+v_i,\ i=1,\ldots,n,$$

where β_0 is the intercept of the model, β_j are the fixed effects of the model, f_k denote any smooth effects, and v_i represents unstructured error terms (random variables).

Commercial validation of the DSS to initiate fungicide applications

From the field observations, early primary PPM symptoms were observed at approximately 240 ADD in average (actually, 241.2 ± 13.1 ADD). Moreover, an average incidence of 0.05 was estimated at 239.1 ± 18.1 ADD with the beta regression model described here. Thus, an operating alert threshold to initiate fungicide applications was chosen at 220 ADD. This value was chosen considering logistic constraints at farm level to let growers a reasonable period to initiate the fungicide sprays. Roughly, this 20 ADD difference were equivalent to approximately 2 days, as DD values observed in this period were about 10 DD a day.

Six orchards, namely 2, and 8 to 12 (Table 2), were used in this study. In each orchard, three fungicide programs were evaluated: i) the standard, calendar-based, fungicide program, which was applied under farmers' criteria and coinciding with the European Directive on Sustainable Use of Pesticides (2009/128/EC). This program was applied in all orchards after petals fall, well before the 220-ADD alert; ii) the fungicide program starting at the 220-ADD alert, which was further continued on a calendar basis, and with same applications and dates as the standard; and 3) the control, non-treated group of trees. Each experimental unit consisted of five contiguous trees which were surrounded by 1-2 rows of untreated trees to avoid spray drift. The selection of fungicides to be used in each application time, as well as the application times based on calendar, were left to each farmer's criteria, but were the same in the calendar-based and after the 220-ADD alert spray program conducted in each orchard. Fungicides used in the orchards during the commercial validation were included in the chemical families of triazoles, dithiocarbamates, benzamides, strobilurins, pyrimidines, quinolines and inorganic fungicides.

The ADD values were calculated daily as described above for all experimental orchards starting at 50% blooming date, the latter being in the range 7 to 9 March 2017. When the 220-ADD alert was approaching (i.e., around 200 ADD; from 18 to 24 April 2017), incidence of PPM was evaluated in all combinations of fungicide programs and orchards. At the end of the experimental period, when no further disease progression was observed (values from 570 ADD to 760 ADD; from 8 to 12 June 2017), incidence of peach powdery mildew was again assessed in all experimental sites and trees.

Statistical analyses

The beta regression to model the dynamics in the proportion of affected fruits was fitted following a Bayesian hierarchical approach with the INLA methodology (Rue et al. 2009). This methodology uses Laplace approximations (Tierney and Kadane 1986) to get the posterior distributions in Latent Gaussian models (LGMs) (Rue et al. 2009). Vague Gaussian distributions were used here for the parameters involved in the fixed effects $\beta_j \sim N(0, 10^{-5})$. Precision of the beta distribution (ϕ) was reparametrized as $\phi = \exp(\alpha)$ to ensure that ϕ was a positive parameter. We assumed pc-priors on the log-precision for both parameters. The computational implementation R-INLA (Rue et al. 2009) for R (R Core Team 2018) was used to perform approximate Bayesian inference. In order to conduct the analysis in our data, values of the response variable were transformed to be in the interval (0,1) dividing by the maximum for each orchard and year. For the shake of simplicity, data were represented in their original units. As common practice in beta regression, 0s and 1s were settled to 0.01 and 0.99 respectively.

In the commercial validation experiment, disease incidence data at the end of the experimental period were analyzed with a logistic regression and binomial distribution. Fungicide programs (i.e., calendar-based, 220-ADD alert and non-treated control) were considered as a fixed factor and orchards as a random blocking factor. The non-treated control was used as the reference level and the odds ratios for the calendar-based and 220-ADD alert spray programs were calculated including their corresponding 95% credibility intervals. R-INLA for R was used to perform approximate Bayesian inference with the prior distributions provided by default.

RESULTS

Dynamics of powdery mildew symptoms on fruits

Only datasets with final PPM incidence on fruit equal or higher than 0.05 in the orchards were used in this study; i.e., a total of 14 datasets resulting from the combination of the experimental orchards and monitored years (Fig. 1). Final incidence values ranged among orchards and years between 0.05 and 0.96. Four orchard-year combinations were in the range 0.05-0.20 final PPM incidence, eight in the range 0.20-0.60, and two over 0.80 (Fig. 1). Moreover, first symptoms were noticed at variable dates and their equivalent ADD values among orchards and years. Field observations revealed that first PPM occurrences on fruit were noticed in average at 240 ADD after the 50 % blooming biofix (mean ± std. err.: 242.0 ± 13.1 ADD; median: 241). On a calendar basis, most of these primary infection symptoms were noticed between the last week of April and the two first weeks of May. PPM incidence increased in the experimental orchards roughly until June, and last new infections were mostly detected at 460-480 ADD (median: 460 ADD; mean 484 ± 42.2). Last new infections on fruit were early detected in May (first to third week) in some orchard-year combinations, whereas in other cases they were detected as late as in July (first week).

The beta regression models were able to accommodate the dynamics of PPM incidence in all the orchards and years analyzed, despite the large differences observed in disease progress rates and final incidences (Fig. 1). The mean of the posterior distribution for the intercept (β_0) ranged from -12.2 in orchard 3 to -4.9 in orchard 2 in 2013, from -16.8 in orchard 1 to -5.2 in orchard 7 in 2014, and from -11.7 in orchard 8 to -4.6 in orchard 6 in 2015 (Table 3). The mean of the posterior distribution for the parameter of ADD (β_1) ranged from 1.6 in orchard 2 to 6.1 in orchard 3 in 2013, from 1.7 in orchard 7 to 5.9 in orchard 1 in 2014, and from 1.3 in orchard 6 to 3.8 in orchard 8 in 2015 (Table 3).

Based on the beta regression models, between 107.2 ADD (orchard 2, 2013) and 278.1 ADD (orchard 1, 2013) were needed to reach PPM incidences of 0.01 in the 2013-15 monitoring period (Table 4). In addition, between 161.6 ADD (orchard 7, 2014) and 389.9 ADD (orchard 1, 2013) were needed to reach 0.10 PPM incidence in the same period. Highest annual mean values for ADD estimations at 0.01 to 0.10 incidence were obtained in 2015, whereas lowest estimates were obtained in 2014. On average, 187.1 to 264.0 ADD were needed to reach PPM incidences between 0.01 and 0.1, respectively, among orchards and years (Table 4). An average of 239.1 ADD for 0.05 PPM incidence was determined for all orchard and year combinations, which was comparable with the first PPM occurrences visually noticed in the orchards.

Commercial validation of the DSS to initiate fungicide applications

Two of the six orchards evaluated in 2017, namely orchards 9 and 12, were excluded from the commercial validation as no PPM symptoms were recorded at the end of the experimental period. Thus, only data from four orchards (2, 8, 10 and 11) were used in the analyses (Supplementary Fig. S1). Disease incidence values recorded in the non-treated control ranged from 0.1574 (orchard 8) to 0.4105 (orchard 2). Mean PPM incidence recorded in the non-treated control was 0.2441 ± 0.1136 (std. dev.) (Fig. 2), with a total sample size of 5894 fruits. Mean

PPM incidence recorded in the calendar-based spray program was 0.0488 ± 0.0323, with a total sample size of 5465 fruits. Mean PPM incidence recorded in the 220-ADD alert spray program was 0.0728 ± 0.0442, with a total sample size of 5883 fruits.

The odds ratio was 0.1992 (credibility interval: 0.1752-0.2250) for the calendar-based spray program and 0.1159 (0.0987-0.1346) for the 220-ADD alert spray program. The 95% credibility interval of the odds ratio was lower than 1, so both spray programs reduced PPM incidence compared with the reference level (non-treated control). The odds of PPM incidence in the calendar-based spray program were 8.63 times less than in the non-treated control, whereas the odds corresponding to the 220-ADD alert spray program were 5.02 times less than in the control. The 95% credibility intervals of the odds ratio for the calendar-based and the 220-ADD alert spray programs did not overlap, being lower for the calendar-based treatment. Therefore, higher reduction of PPM incidence compared with the non-treated control was obtained with the calendar-based spray program than with the 220-ADD alert spray program.

Regarding the total number of fungicide applications in the calendar-based program, it ranged from 4 (orchard 2 and 10) to 7 (orchard 8). Meanwhile, the number of fungicide applications in the 220-ADD alert spray program ranged from 2 (orchard 10) to 5 (orchard 8). This represents, in percentage, and compared with the calendar-based program, a reduction in the numbers of fungicide applications from 25% (orchard 2) to 50% (orchard 10) (mean: 33.3%) (Supplementary Table S1).

DISCUSSION

The incidence of peach powdery mildew on peach and nectarine fruits was monitored in different commercial orchards located in Catalonia, Northeast Spain, along several years. This allowed us to describe the disease progress in relation to air temperature, which has been reported to be one of the main factors affecting the disease progress in powdery mildews (Yarwood 1957). Temperature was expressed in ADD recorded after the 50 % blooming biofix, and PPM progression was modelled according to ADD using beta regression models (Ferrari and Cribari-Neto, 2004). As shown by previous studies using beta regression for modelling inoculum availability of *Plurivorosphaerella nawae* (Martínez-Minaya et al., 2019), this method overcomes the drawbacks of the traditional data transformations, allowing a direct interpretation of model parameters in terms of the original data. The analysis is not sensitive to the sample size and posterior distributions are expected to concentrate well within the bounded range of proportions.

Butt (1978) pointed out that powdery mildews are underrepresented in conceptual epidemiological models, partly because their disease cycles are not driven by a critical environmental variable such as wetness. In addition, the advent of fungicides with notable activity against powdery mildews may also have averted the reliance on epidemiological models to schedule fungicide sprays. Nevertheless, a reduction in fungicide use and implementation of DDSs is now mandatory by Directive 2009/128/EC, which aims at establishing a global framework on the sustainable use of pesticides in the EU.

Previous works on modelling *P. pannosa* progression on fruits are scarce in literature; some models aimed to determine optimal temperature and relative humidity parameters for different phases of the disease cycle (Grove 1995; Toma and Ivascu, 1998). However, Pieters et al. (1993) concluded that neither the temperature nor the relative humidity influenced the differentiation between the two epidemic phases (primary and secondary infections) that were described for *P. pannosa* progression on rose in greenhouse conditions. Regarding the control of rose powdery mildew, Pieters et al. (1993) also concluded that initiating fungicide applications between the two epidemic phases reduced total fungicide inputs for disease control.

Several epidemiological models for powdery mildew in other host species described the relationship between environmental factors and specific stages of the disease cycle, such as the occurrence of secondary infections of wheat powdery mildew (Cao et al. 2015), or the optimal conditions for spore germination and infection in apple (Xu 1999). Other models consisted of several components, which included different environmental variables to describe in detail the disease progress along the crop cycle and give advice to farmers on proper fungicide spray timing. For instance, the Gubler-Thomas model for the grapevine powdery mildew (Gubler et al. 1999) predicts disease pressure and consists of two components according to the disease cycle: an ascospore primary infection and a conidial secondary infection stage. The first component of the model predicts the release of ascospores (primary inoculum) and infections depending on rain, temperature and wetness periods, whereas the second component turns to be a risk index for secondary conidial infections based on the effects of temperature and wetness duration variables. Similar approaches have been developed for the management of cherry powdery mildew (Grove 1991; Grove and Boal 1991; Grove 1998), which are, to the best of our knowledge, the only example of epidemiological models previously described for Rosaceae species. The effects of several meteorological factors on the development of different stages of the cherry powdery mildew have been studied, such as the release and germination of ascospores depending on temperature and wetness duration (Grove 1991), the germination of conidia on leaves and fruits depending on the temperature and vapour pressure deficit (Grove and Boal 1991), and the availability of the secondary inoculum based on temperature, relative humidity and wind speed (Grove 1998). In a posterior study, Grove et al. (2000) used the secondary infection component of the Gubler-Thomas model in the management of cherry powdery mildew infections with spray oils.

Carisse et al. (2009) developed and validated a degree-day model to initiate a fungicide spray program for the management of grapevine powdery mildew. They concluded that fungicide sprays could be initiated when 1 % to 5 % of the total seasonal airborne inoculum was reached, which was depending on the grape variety about 500-600 ADD after vines reached the 2–3 leaves phenological stage. According to this degree-day model, fungicide sprays were initiated 30 to 40 days later than those in the standard program (just at the 3–4 leaves phenological stage). This resulted in a 40-55 %. reduction in the number of fungicide sprays applied. Similarly, we were able to establish a fungicide spray program based on the degree-day monitoring with an operating threshold of 220-ADD to initiate fungicide applications, allowing farmers with a safe period to coordinate spray logistics before the onset of the risk period.

For the defined 220-ADD operating threshold, the beta regression model estimated a PPM incidence between 0.02 and 0.05 (i.e., between 205.3 and 239.1 ADD). Thus, 220-ADD spray program is based on synchronizing the initiation of fungicide applications with the detection of the first PPM symptoms. This period coincides with the beginning of the exponential phase of the disease, which causes significant yield losses in grapevine (Carisse et al. 2009). Nevertheless, the 220-ADD alert spray program resulted in an increase of 2.4 % final PPM incidence as compared to the calendar-based program. Although statistically relevant because of the relatively large sample size, the size effect of this difference was not biologically substantial in our opinion and, thus, we consider the 220-ADD alert spray program as effective as the current calendar-based spray program.

Fungicide sprays in the 220-ADD alert spray program were initiated 24 to 39 days later than in the calendar-based spray program, resulting in an overall reduction of 33 % in the number of fungicide applications. Estimated local cost per each fungicide application (including fungicide, machinery and personnel costs) in the commercial orchards of our study ranged from 70 to 90 $ per ha and application (Marimon, *unpublished data*). Thus, the 220-ADD alert spray program represents a valuable tool to optimize PPM control by reducing both production and environmental costs.

Further validations would be needed to extrapolate the 220-ADD alert spray program for PPM management to other cultivars and growing areas with different environmental conditions. For instance, disease prediction could be adapted by considering cultivar susceptibility and inoculum levels present in the orchard, as they were also considered by Carisse et al. (2009) in the case of the grapevine powdery mildew. Also, other variables might be considered in the current model in addition to temperature. We aimed at describing the PPM progress by using a simple model with few variables. Thus, we focused on air temperature as this variable is widely available and can be easily recorded at orchard level. Also, DSSs based on this environmental variable are more accessible and easier to implement by farmers (Jarvis et al. 2002). Despite of the potential advantages foreseen by the implementation of the 220-ADD alert spray program, we assume that epidemiological models including only one or few components of the disease cycle may limit, to some extent, model transferability and consistency. Therefore, further work is needed with PPM models including additional environmental predictors for the primary and secondary infections on peach fruit. In this sense, the 220-ADD operating threshold described here may be considered as the first component of a future, more complete, DSS for powdery mildew control on peach.

Diversification of fungicides and usage of resistant cultivars are the main management strategies used for powdery mildew management worldwide (Cao et al. 2015; Wolfe 1984). Nowadays, epidemiological models and derived DSSs are also important in integrated disease management. Combining the use of resistant cultivars with effective DSSs would certainly reduce the amount of fungicides applied while maintaining optimal disease control levels.

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TABLES

Table 1. Characteristics of the commercial orchards used in the study of the disease progression of peach powdery mildew on fruit (2013-15), and the commercial validation of the model to initiate the seasonal applications of fungicides (2017).

Orchard no.	UTM Coordinates (WGS 84, 31 T)		Area (ha)	Crop	Cultivar	Rootstoc k	Tree spacing (m)	Symptom monitorin g (years)	Commercial validation (year)
	X	*Y*							
1	287680	4602661	4.18	Nectarine	‘Red Jim’	‘GF-677’	5 x 3	2013-2015	
2	297674	4602928	0.95	Nectarine	‘Red Jim’	‘GF-677’	5 × 3	2013-2015	2017
3	289237	4613448	0.73	Peach	‘Albesa Red’	‘GF-677’	5 x 3	2013-2014	
4	288554	4613923	8.96	Platerine	‘ASF 07.78’	‘GF-677’	5 x 3	2015	
5	283489	4619988	1.00	Nectarine	‘Venus’	‘GF-677’	5 x 3	2013	
6	302991	4627916	6.96	Nectarine	‘Nectareine’	‘GF-677’	4.5 x 2.5	2014-2015	
7	287918	4597751	4.59	Nectarine	‘Venus’	‘GF-677’	5 x 3	2013-2014	
8	287141	4609517	3.71	Nectarine	‘Autumn free’	‘GF-677’	4.5 × 2.5	2013-2015	2017
9	287972	4603490	4.62	Nectarine	‘Tarderina’	‘GF-677’	5 x 2.9		2017
10	286696	4605773	4.14	Nectarine	‘Independence’	‘Garnem’	5 x 3		2017
11	289380	4612041	4.96	Nectarine	‘Extreme Red’	‘GF-677’	4 x 2		2017
12	282806	4614805	0.86	Nectarine	‘Nectatinto’	‘GF-677’	5 x 3		2017

Table 2. Most relevant dates and accumulated degree days (ADD) values recorded during the commercial validation of the 220-ADD alert spray program for the control of peach powdery mildew in 2017 in six nectarine orchards.

Orchard no.	50% bloom date	Petals fall	220-ADD alert Pre-evaluation		Application at 220-ADD alert		Final evaluation	
			Date	ADD	Date	ADD	Date	ADD
2	8 Mar	15 Mar	21 Apr	214.9	22 Apr	219.4	9 Jun	654.2
8	7 Mar	13 Mar	18 Apr	207.9	21 Apr	222.7	9 Jun	636.3
9	7 Mar	15 Mar	19 Apr	228.6	20 Apr	232.8	8 Jun	675.2
10	7 Mar	29 Mar	21 Apr	213.5	22 Apr	219.4	12 Jun	648.4
11	9 Mar	21 Mar	21 Apr	222.7	20 Apr	216.9	12 Jun	758.9
12	8 Mar	30 Mar	24 Apr	208.1	27 Apr	217.8	8 Jun	572.8

Table 3. Posterior distributions for the parameters (β_0, β_1) of the beta regression model on the peach powdery mildew disease progression modelling for different orchards and years, including mean, 95% credibility interval and standard deviation.

Year	Orchard	β_0 (Intercept)				β_1 (ADD)			
		Mean	0.025 quant	0.975 quant	Std. deviation	Mean	0.025 quant	0.975 quant	Std. deviation
2013	1	-12.0	-16.9	-7.7	2.3	3.6	2.3	5.0	0.7
	2	-4.9	-6.2	-3.6	0.7	1.6	1.2	2.0	0.2
	3	-12.2	-18.0	-7.6	2.7	6.1	3.7	9.0	1.3
	5	-9.2	-12.5	-6.3	1.6	2.6	1.8	3.6	0.5
	7	-8.3	-11.5	-5.4	1.5	3.6	2.4	5.1	0.7
	8	-6.4	-9.3	-3.9	1.4	2.3	1.4	3.4	0.5
2014	1	-16.8	-24.2	-10.7	3.5	5.9	3.7	8.5	1.2
	2	-6.4	-8.0	-4.8	0.8	2.4	1.8	3.0	0.3
	6	-7.1	-10.0	-4.5	1.4	3.6	2.3	5.1	0.7
	7	-5.2	-7.0	-3.6	0.9	1.7	1.2	2.2	0.3
	8	-13.7	-19.2	-9.0	2.6	4.3	2.9	5.9	0.8
2015	1	-7.7	-10.7	-5.2	1.4	2.4	1.7	3.3	0.4
	6	-4.6	-6.2	-3.1	0.8	1.3	0.9	1.8	0.2
	8	-11.7	-17.2	-7.2	2.6	3.8	2.3	5.5	0.8

Table 4. Accumulated degree-days calculated by the beta regression model for the studied orchards and years combinations when the incidence of peach powdery mildew in fruit was 0.01, 0.02, 0.05 and 0.1.

Year	Orchard	Disease incidence			
		0.01	**0.02**	**0.05**	**0.1**
2013	1	278.1	296.3	327.9	389.9
	2	107.2	138.0	181.0	230.0
	3	180.6	195.9	n.a.	n.a.
	5	246.1	264.1	293.4	327.5
	7	141.0	149.2	164.3	180.4
	8	166.4	187.0	221.6	261.6
Mean 2013		186.6	205.1	237.6	277.9
2014	1	255.7	267.6	291.2	n.a.
	2	131.2	146.7	177.6	208.4
	7	112.7	123.3	141.6	161.6
	6	260.0	271.2	291.6	315.0
	8	114.3	131.0	163.2	200.4
Mean 2014		174.8	188.0	213.0	221.4
2015	1	205.8	225.4	260.8	296.6
	6	270.4	290.8	336.0	n.a.
	8	150.4	188.4	257.7	333.0
Mean 2015		208.9	234.9	284.8	314.8
Total means		**187.1**	**205.4**	**239.1**	**264.0**

n.a.: not applicable.

FIGURE CAPTIONS

Figure 1. Dynamics of peach powdery mildew incidence in fruit (solid dots) and accumulated degree-days in the orchards evaluated from 2013 to 2015. Median posterior distribution (solid line) and 95% credibility interval (shaded area) obtained with the beta regression models.

Figure 2. Peach powdery mildew incidence obtained with a calendar-based fungicide program, fungicide applications initiated after 220 accumulated degree days (ADD), and a non-treated control evaluated in 2017 in a commercial validation. Error bars stand for standard deviation of the mean

Figure 1.

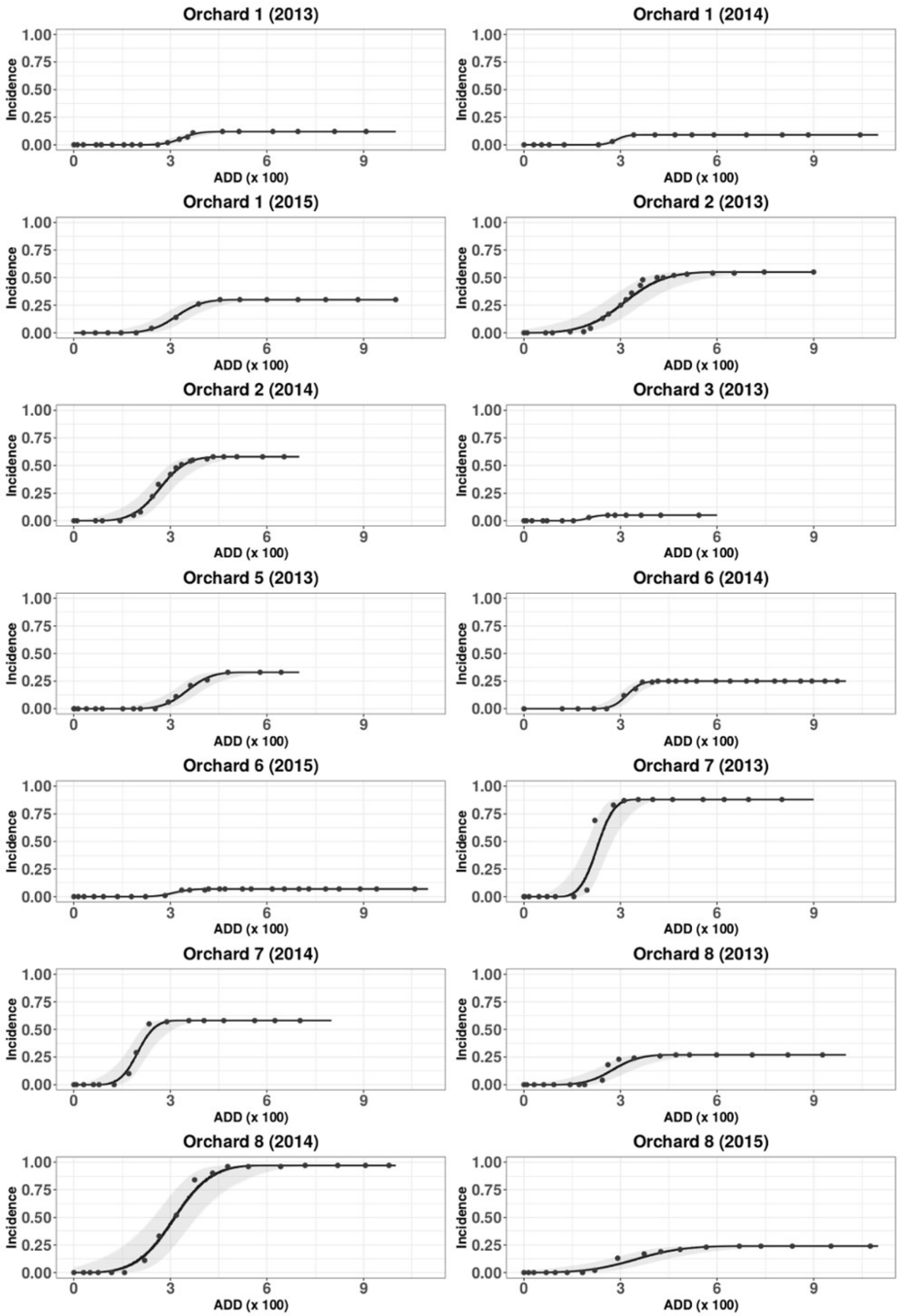
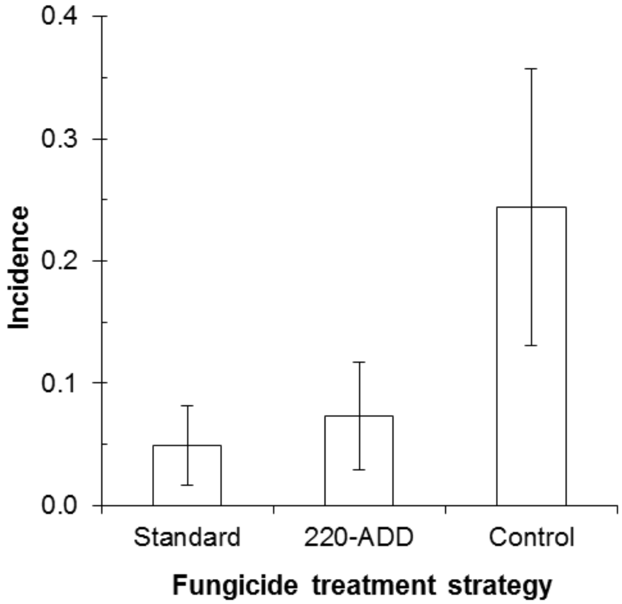

Orchard 1 (2013)
Orchard 1 (2014)
Orchard 1 (2015)
Orchard 2 (2013)
Orchard 2 (2014)
Orchard 3 (2013)
Orchard 5 (2013)
Orchard 6 (2014)
Orchard 6 (2015)
Orchard 7 (2013)
Orchard 7 (2014)
Orchard 8 (2013)
Orchard 8 (2014)
Orchard 8 (2015)
Incidence
0.00
0.25
0.50
0.75
1.00
ADD (x 100)
0
3
6
9

Figure 2.


0.4
0.3
0.2
0.1
0.0
Incidence
Standard
220-ADD
Control
Fungicide treatment strategy

e-Xtras

Supplementary Table S1. Number of fungicide applications before and after the 220-ADD threshold was reached in four experimental orchards evaluated for the model validation. The percentage of application reduction is indicated for each orchard.

Orchard no.	**Applications**		**Application reduction (%)**
	Before 220-ADD	**After 220-ADD**	
2	1	3	25.0
8	2	5	28.6
10	2	2	50.0
11	2	4	33.3
Total	7	14	33.3

Supplementary Figure S1. PPM incidence in four experimental orchards where three different calendar strategies for fungicide application were tested.