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ORIGINAL PAPER

An agro-climatic approach to determine citrus postbloom fruit drop risk in Southern Brazil

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Abstract Postbloom fruit drop (PFD) causes lesions on the petals of citrus flowers and induces fruit abscission causing severe damage to production when the flowering period coincides with intense rainfall. The aims of this study were to develop a phenological-climatological model for citrus PFD occurrence and, together with weather data series from several locations, to determine and map the agro-climatic favorability of PFD occurrence in the state of São Paulo, Southern Brazil. A phenological flowering model was developed to identify when citrus flowering occurs. The flowering starts after when a temperature below 10 °C in the months of June or July is reached followed by cumulative rainfall within 5 days of at least 20 mm, and then 96 °C days. Between the beginning of flowering and its peak, 147 °C days are required, and between the peak and its end, approximately 229 °C days, being 206 °C days from the peak to the moment when flowers remaining are about 50 % of total. The relationship between PFD incidence and accumulated rainfall during the critical period (between flowering peak and 50 % of flowers remaining) was adjusted by the Gompertz model ($R^2=0.99$, $p<0.05$). After its validation, this model was used to estimate PFD incidence for 29 locations in the state, from 1993 to 2013, which allowed to map the PFD climatic favorability for the state through a Geographical Information System using linear models based on latitude, longitude, and altitude. The obtained map showed a trend of PFD incidence increasing from the northwest of the state of São Paulo towards the south and the coastal region, with medium to very high favorability in the center of the state. The results of this study can be used by growers as a guide for disease control planning as well as for defining the regions where the climatic conditions are likely to escape this disease.

Keywords Disease risk assessment · Phenological model · Gompertz model · Orange orchards

Introduction

The Brazilian citrus sector, along with the USA, is responsible for 90 % of the production of orange juice in the world. In Brazil, the state of São Paulo has about 72 % of domestic production, totaling approximately 14,100 tons (IBGE 2015). The orange orchards are concentrated in the northern and northeastern regions of the state of São Paulo, representing 65 % of the Brazilian production area. The southwestern region of the state contributes to 15 % of the citrus-producing area; however, it has undergone an extensive increase in the last 10 years, of about 80–90 %. This migration has been due mainly to lower land costs, and better rainfall distribution throughout the year, which both eliminates the requirement of irrigation and reduces the risks of major diseases, such as huanglongbing (HLB) and citrus variegated chlorosis (CVC) (Neves 2010).

This expansion of the citrus-producing areas to the southern region of the state of São Paulo has reduced the risk of the abovementioned diseases, but, on the other hand, the climatic conditions of this new region are extremely favorable to

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postbloom fruit drop (PFD), mainly when flowering coincides with the rainfall events (Feichtenberger 1994).

In Brazil, PFD, caused by *Colletotrichum acutatum*, has been reported since the 1970s, first in the orchards of the state of Rio Grande do Sul and later in the state of São Paulo (Porto et al. 1979). A survey of *Colletotrichum* associated with symptoms of PFD in the state of São Paulo showed *Colletotrichum gloeosporioides* in addition to *C. acutatum* (Lima et al. 2011). In the state of São Paulo, PFD caused damage mainly in the growing seasons of 1977/78 (Rossetti et al. 1981), 1990/91 (Feichtenberger 1991), 1993 (Feichtenberger 1994), 1996, and 1998 (Peres et al. 2000). The region most affected by the disease was the southwest, although it has been observed in other regions (Feichtenberger 1991; Feichtenberger 1994).

PFD symptoms appear as brownish or orange spots on petals, which subsequently turn to a salmon color due to the formation of fungus fruiting bodies (acervuli). When environmental conditions are favorable, the lesions develop rapidly, affecting the entire petal, which makes the open flowers more susceptible to the infection. As a result of the infection, there is yellowing of the newly formed fruits that stand out from the base of the ovary and fall, leaving adhered to the branch a plant structure commonly called buttons or more formally "persistent calyces" (Timmer et al. 1994). Epidemics of PFD occur suddenly and become explosive (Timmer et al. 1994), which indicate a high dispersal efficiency that is potentially related to an alternative mechanism for inoculum dissemination. The incubation period of the disease can vary from 2 to 5 days, depending on weather conditions (Denham and Waller 1981; Timmer 1990). Agostini et al. (1995) observed greater increases of PFD associated with rainfall exceeding 20 mm.

As citrus PFD occurs during flowering and its severity in a given cultivar and location varies with the length of flowering period, it is extremely important to determine flowering period and which factors influence its beginning, peak, and end. A previous study about the citrus-*Colletotrichum* sp. pathosystem showed that the flowering period is influenced by both temperature and rainfall (Ribeiro et al. 2006).

Studies of historical rainfall data to estimate spray requirements and to evaluate the climate risk for a given disease by combining different agrometeorological techniques have enabled maps to be drawn that enhance the viewing of disease distribution and areas of risk (Lozada Garcia 2005), which make possible to evaluate different strategies of control.

To better express the distribution of plant diseases in a given area, the term geophytopathology was created by Weltzien (1972). This technique allows for visualizing how the disease is spread in a geographical space and establishes relationships with climate, vegetation, and soil factors which favor its occurrence, so as to bring to light the cause of these distribution patterns. The maps can be classified by location, intensity, area of occurrence, dates of occurrence, and areas of risk or escape (Weltzien 1972).

To create and provide disease risk maps, the use of Geographic Information Systems (GIS), geostatistics, models of disease prognosis, and agrometeorological data is required. Based on the interdependence of the disease and the weather conditions, these disease risk maps can help in the evaluation of strategies for crop establishment and disease management (Ghini et al. 2011).

Based on the high interdependence between PFD occurrence and climatic conditions, this study aimed to develop a phenological-climatological model for citrus PFD occurrence and, together with weather data series from several locations, to determine and map the agro-climatic favorability zones for this disease in the state of São Paulo, Southern Brazil.

Materials and methods

The present study was developed following, basically, seven steps: (a) flowering and PFD data survey, (b) development of a phenological model for flowering occurrence and duration, (c) development of an empirical model to estimate a PFD as a function of weather data, (d) validation of the PFD empirical model, (e) estimation of PFD for several locations in the state of São Paulo and development of a multivariate model to correlate it to geographical coordinates and altitude, (f) elaboration of a PFD favorability map for the state of São Paulo by applying the multivariate model, and (g) test of the map by simple and cross-validation procedures.

Phenological model for citrus flowering

The flowering dates and weather data used in this step were obtained from experiments conducted in Itapetininga for Natal and Pera orange cultivars (Peres et al. 2004) and in Santa Cruz do Rio Pardo for Valencia and Pera orange cultivars (Silva Júnior 2011).

The timing of flower phenological stages was assumed to depend upon the accumulation of heat units; thus, a physiological time scale in degree-days (°C day) was used for developing the model.

Growing degree-days (GDD) is defined as the number of degrees of temperature above a certain base temperature, which varies among crop species and cultivars. The base temperature is the one below which plant development is zero. GDD are calculated for each day as the difference between daily mean and base temperatures. GDD are accumulated by adding each new daily GDD contribution as the season progresses. For oranges, root, shoot, and fruit growth and development slow considerably below 13 °C (Bevington and Castle

1986), value that was used as the base temperature for calculating GDD in the present study.

The agro-climatic model for estimating flowering date and flowering duration was developed by assuming that the process begins on a variable calendar date each year between June and July and that they require a constant number of degree-days for completion.

The date for starting the accumulation of degree-days and the average number of degree-days from this date to the bloom peak, 50 % of remaining flowers, and end of petal fall were estimated for the flowering of Pera, Natal and Valencia cultivars. As flowering also depends on water, daily rainfall data were accumulated for different sub-periods of the flowering phase for the same cultivars.

After the determination of the phenological model for Itapetininga and Santa Cruz do Rio Pardo, the citrus flowering stages were estimated for 29 locations in the state of São Paulo (Table 1), in the major citrus-producing areas of the state. Daily minimum and maximum air temperature and rainfall for the last 21 years (1993–2013) were obtained from the following databases: the Integrated Center of Agrometeorological Information (CIIAGRO), the Brazilian National Institute of Meteorology (INMET), Agritempo/EMBRAPA, and the Department of Water and Energy of the state of São Paulo (DAEE/SP).

Survey of citrus PFD in the state of São Paulo

A survey was conducted to identify PFD occurrence and intensity data and the respective climatic conditions during the flowering period in a number of locations in the state of São Paulo. These data were obtained from different years with varying PFD intensity by Peres et al. (2004), Cintra (2009), Rinaldo (2010), Spada (2011), and Silva Júnior (2011) (Table 2). As the PFD symptoms were evaluated by different methods, we converted the data presented by these authors to

Table 1 Locations in the state of São Paulo used in this study with their respective geographical coordinates and altitude and climatic series considered

Locations	Latitude (S)	Longitude (W)	Altitude (m)	Series
Adamantina	21.6°	51.0°	417	1993–2013
Andradina	20.9°	51.4°	366	1995–2013
Araçatuba	21.2°	50.5°	390	1996–2013
Assis	22.7°	50.4°	578	1993–2013
Bauru	22.2°	49.2°	510	1995–2013
Bebedouro	20.9°	48.5°	557	1993–2013
Botucatu	22.8°	48.4°	792	1994–2013
Cristais Paulista	20.4°	47.4°	983	1993–2013
Guaíra	20.3°	48.3°	520	1993–2013
Itararé	24.1°	49.3°	702	1993–2013
Jales	20.3°	50.6°	420	1994–2013
Jundiaí	23.2°	46.9°	778	1994–2013
Limeira	22.6°	47.4°	590	1995–2013
Lins	21.6°	49.7°	433	1995–2013
Marília	22.2°	50.0°	629	1993–2013
Matão	21.6°	48.4°	612	1993–2013
Mirante do Paranapanema	22.4°	52.0°	369	1995–2013
Mococa	21.4°	47.1°	613	1993–2013
Pindamonhangaba	22.8°	45.5°	668	1993–2013
Presidente Prudente	22.1°	51.4°	434	1993–2013
Registro	24.5°	47.8°	25	1995–2013
Ribeirão Preto	21.2°	47.8°	567	1993–2013
Santa Cruz do Rio Pardo	22.8°	49.6°	558	1993–2013
São José do Rio Preto	20.8°	49.4°	522	1994–2013
São Paulo	23.6°	46.6°	799	1997–2013
Tatuí	23.3°	47.8°	607	1993–2013
Tupã	22.0°	50.6°	479	1993–2013
Ubatuba	23.4°	45.1°	11	1993–2013
Votuporanga	20.4°	50.0°	499	1993–2013

Table 2 Occurrence of citrus PFD in different locations in the state of São Paulo, Brazil, and their respective years, intensity, and meteorological conditions between bloom peak and 50 % of remaining flowers

Location	Year	Relative PFD intensity	Average temperature (°C)	Total rainfall (mm)
Itapetininga[a]	1999	Zero	19.4	0.0
Itapetininga[a]	2000	Zero	20.0	10.0
Itapetininga[a]	2001	Medium-high	19.2	118.0
Itapetininga[a]	2002	Low	20.3	49.0
Itapetininga[b]	2007	Low	17.4	4.9
Itapetininga[b]	2008	Medium-high	21.5	78.8
Santa C. R. Pardo[c]	2009	High	23.0	112.0
Capela do Alto[d]	2009	High	19.8	137.0
Bofete[d]	2009	High	20.2	193.0
Pardinho[d]	2009	High	20.1	194.0
Santa C. R Pardo[e]	2008	Low	22.5	12.0
Santa C. R. Pardo[e]	2009	High	22.0	116.0
Santa C. R. Pardo[e]	2010	Medium	24.6	62.0
Santa C. R Pardo[e]	2009	High	19.0	116.0
Santa C. R. Pardo[e]	2010	Zero	22.8	0.5
Taquarituba[e]	2009	Low	19.6	42.2
Taquarituba[e]	2010	Low	18.6	12.4

[a] Peres (2002)

[b] Cintra (2009)

[c] Rinaldo (2010)

[d] Spada (2011)

[e] Silva Júnior (2011)

relative disease intensity, in order to correlate them with climatic data.

Relationship between PFD incidence and accumulated rainfall during the flowering period

After the determination of the flowering period by the proposed model, the accumulated rainfall observed in 2008, 2009, and 2010 in Santa Cruz do Rio Pardo was submitted to a comparative analysis for the specific years in which the PFD outbreaks occurred. These analyses were conducted for the period of the year when the conditions were best for PFD, which corresponded to June–November in Santa Cruz do Rio Pardo.

The exponential, monomolecular, logistic, and Gompertz non-linear models were tested to adjust the relationship between PFD incidence and cumulative rainfall during the abovementioned flowering period for Valencia, Natal, and Pera cultivars: between bloom peak and the end of bloom and between bloom peak and 50 % of remaining flowers.

These non-linear models are described by the following equations: exponential $y=b_1 \times \exp(b_2 \times x)$, monomolecular $y=b_1 \times (1-b_1/b_2) \times \exp(x \times -b_3)$, logistic $y=1/(1+b_1 \times \exp(b_2 \times x)$, and Gompertz $y=\exp(-b_1 \times \exp(-b_2) \times x)$, and were analyzed by the STATISTICA software program (version 7.0, StatSoft, Tulsa), where y is the percentage of plants affected by PFD; x is the accumulated rainfall (mm); and b_1, b_2, and b_3 are the statistical coefficients of the models. The choice of the best adjusted model was made by analyzing the coefficient of determination (R^2), standard errors, and the distribution of residues (Campbell and Madden 1990). The validation of the proposed PFD incidence model was performed using independent experimental data obtained by Agostini et al. (1993), Timmer and Zitko (1995), and Timmer and Zitko, 1996) in Florida, USA, and by Klein et al. (2013) in Estiva Gerbi, São Paulo, Brazil.

Using algebraic techniques for mapping (Tomlin 1990), the estimating beginning dates of flowering, the estimating flowering duration, and the duration between bloom peak and 50 % of remaining flowers in the state of São Paulo were converted into maps, using the Geographic Information System ArcGIS 9.3, processing the independent variables (latitude, longitude, and altitude) as layers in raster format.

Variability of PFD incidence in the state of São Paulo

Daily minimum and maximum air temperature and rainfall data for the last 21 years (1993–2013) were obtained for 29 locations in the state of São Paulo (Table 2), which represent the major citrus-producing areas of the state. These data were obtained from the sources previously described.

For all locations and years, the flowering period and the sub-period between the bloom peak and 50 % of remaining flowers were determined based on the phenological flowering model and the accumulated rainfall for this sub-period was used to estimate PFD incidence and determine its inter-annual variability, according to the PFD model proposed.

The PFD incidence values obtained by the Gompertz model were divided into classes of favorability of disease incidence, based on the relationship between the incidence of symptomatic flowers and the relative citrus production (percentage) proposed by Silva Júnior (2011) and represented by the equation: $y=97.459\times e^{-0.011x}$, where y is the relative production (proportion) and x the symptomatic flowers (%).

PFD incidence classes were determined by considering their variability and a safety margin for the producer, since the disease is very explosive. The PFD incidence classes were defined as 0–15 % (low favorability), 15.1–30 % (medium favorability), 30.1–50 % (medium-high favorability), 50.1–70 % (high favorability), and >70 % (very high favorability).

PFD favorability map for the state of São Paulo

For spatializing PFD incidence estimated by the proposed model, considering the spatial pattern of variation of this disease according to the weather conditions, a multivariate linear regression model, correlating estimated PFD incidence (Gompertz model) with geographical coordinates (latitude and longitude) and altitude, was generated: $I=a+b*\varphi+c*\lambda+d*h+e*\ \varphi*\lambda+f*\lambda*h+g*\varphi*h+h*\varphi^2+i*\lambda^2+\ j*\ h^2$, where I is the PFD incidence estimated for each location (pixel) in the state of São Paulo, φ is the latitude in decimal degrees (negative values), λ is the longitude in decimal degrees (negative values), h is the altitude in meters, and a to j are the statistical coefficients of the multivariate regression equation.

The selection of the significant independent variables was performed using the SYSTAT software (version 2011), and the best model was selected by the "backward stepwise" using multivariate regression, considering a probability of 10 %. The best model was determined by the coefficient of determination (R^2).

Using algebraic techniques for mapping (Tomlin 1990), the PFD estimated for each pixel by the multivariate regression model was converted into a map of PFD incidence for the state of São Paulo, using the Geographic Information System ArcGIS 9.3, processing the independent variables (latitude, longitude, and altitude) as layers in raster format.

The altitude layer, in meters, was obtained from the digital elevation model (DEM) generated by radar images from "NASA Shuttle Radar Topographic Mission" (SRTM), with pixel resolution of 90×90 m. Layers of latitude and longitude, in decimal degrees, were computed using the central coordinates of each pixel corresponding to the DEM.

Layers of latitude, longitude, and altitude were employed, together with the equation for estimating PFD incidence in relation to the geographical coordinates, using the tool "Spatial Analyst–Raster Calculator" to calculate the incidence for each pixel and obtain the map of PFD incidence. Finally, the results were transformed in a *Shapefile* by the "Data–Export" tool, enabling the maps to be elaborated.

Test of the PFD favorability map

The multivariate linear model was tested to ensure the reliability of this procedure when applied to map estimated PFD incidence for every new cycle of orange production. Two types of validation were performed to verify the reliability of this model for spatializing the estimated PFD favorability in the state of São Paulo, for instance, simple validation and cross-validation.

Simple validation compared PFD incidence estimated by the Gompertz model and that obtained from the multivariate linear model. For this, independent data from 11 locations homogeneously distributed in the state, called test locations (Fig. 1), were employed. For evaluating the performance of the multivariate linear model in this validation, beyond R^2, the following errors were analyzed: mean error (ME), mean absolute error (MAE), root mean square error (RMSE), and the mean absolute percentage error (MAPE), according to the following equations:

$$\mathrm{ME}=\frac{1}{N}\sum(y_i-x_i)$$

$$\mathrm{MAE}=\frac{1}{N}\sum|y_i-x_i|$$

$$\mathrm{RMSE}=\sqrt{\frac{1}{N}(y_i-x_i)^2}$$

$$\mathrm{MAPE}=\frac{100}{N}\sum\left|\frac{y_i-x_i}{y_i}\right|$$

where x_i is the PFD incidence estimated by the Gompertz model, y_i is the PFD incidence estimated by the multivariate linear model, and N is the number of locations considered (=11).

The performance of PFD incidence model was also evaluated by the performance index (P_i). This index is an update of the confidence index c (Camargo and Sentelhas 1997), which corresponds to the product of Pearson's correlation coefficient r and the agreement index d (Willmott et al. 1985). The P_i is the product of r and the refined agreement index dr, combining accuracy and precision (Alvares et al. 2013a). The criteria for

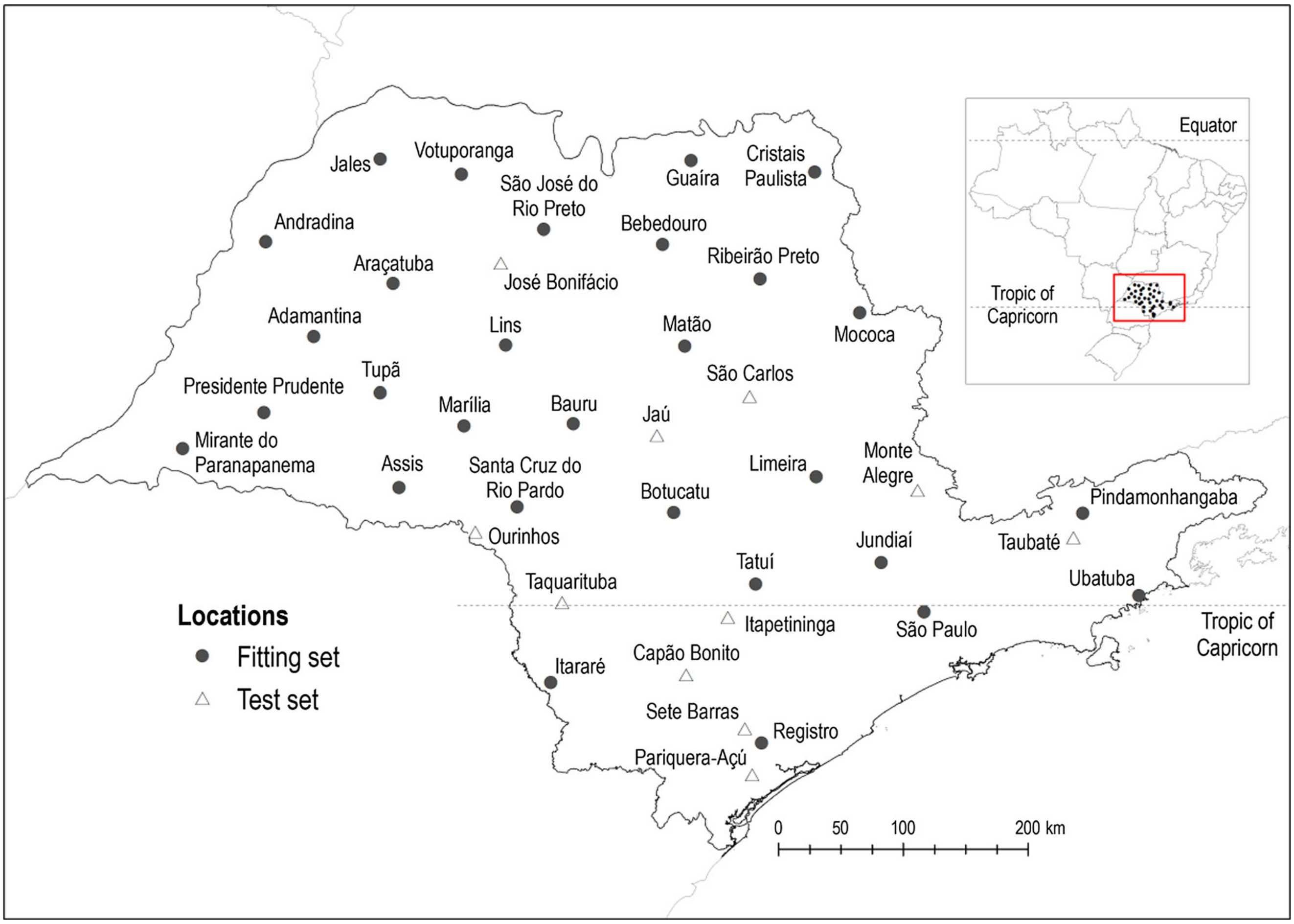

Fig. 1 Locations in the state of São Paulo used for estimating PFD incidence (*filled circles*) and locations used to validate the linear model for estimating the spatial distribution of disease incidence (*open triangles*)

interpreting the performance index (P_i) is as follows: $P_i \geq 0.75$, optimum performance; $0.6 \leq P_i < 0.75$, very good performance; $0.45 \leq P_i < 0.6$, good performance; $0.3 \leq P_i < 0.45$, tolerable performance; $0.15 \leq P_i < 0.3$, poor performance; $0 \leq P_i < 0.15$, bad performance; and $P_i < 0$, very bad performance.

Cross-validation was also employed to confirm the performance of linear models for spatializing PFD incidence. Cross-validation is widely used in studies where the objective is to validate a predictive model. This technique divides the data set into subsets and then use one of these subsets to estimate the model's parameters (training data) and the remaining ones to validate the results (Kohavi 1995).

The cross-validation was performed using all dataset, which corresponds to the 40 locations, being one location removed and used as subset and the remaining 39 for estimating the model parameters. This process was repeated 40 times by alternating the location to be removed from the dataset. At the end of this process, the performance of the model was determined by the same indices and errors described previously for the simple validation.

Results and discussion

Citrus flowering phenological model

The production of citrus plants is determined initially by flowering, which in turn is conditioned by the physiological status of the plants (Goldschmidt et al. 1985) and the environmental conditions (Ortolani et al. 1991).

The importance of temperature as a major factor in flower induction is well established and has long been recognized as such (Moss and Muirhead 1971; Altman and Goren 1974; Valiente and Albrigo 2004; Nebauer et al. 2006). Several authors have proposed that low temperatures may have the dual effect of releasing bud dormancy and inducing flowering (Southwick and Davenport 1986; Tisserat et al. 1990).

After the analysis of previous studies, it was observed that before the onset of flowering, in the state of São Paulo, the following events were necessary: occurrence of a minimum daily temperature below 10 °C between June and July, followed by a cumulative rainfall within 5 days of at least 20 mm, and then an average total of 96 °C days till the bloom (Fig. 2).

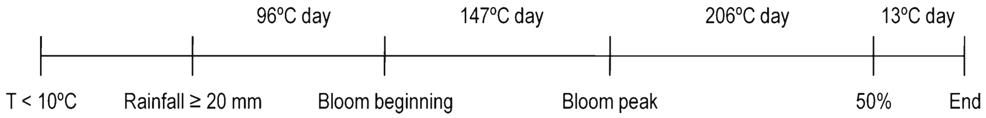

Fig. 2 Representation of the timeline with meteorological/phenological events for the definition of total degree-days for each flowering (bloom) stage considered in this study (beginning, bloom peak, 50 % of remaining flowers, and end) for Natal, Pera, and Valencia oranges

Regarding the induction of flowering in citrus, it is known that, in addition to the importance of low temperatures, rainfall is the main weather variable influencing onset and duration of the flowering period (Tubelis and Salibe 1989; Camargo et al. 1999). During the winter, plant growth decreases due to low soil moisture and air temperature (<13 °C), which induces dormancy (Reuther 1977). This situation provides a stimulus for the transformation of vegetative buds into reproductive ones, and this balance is probably regulated by hormonal changes (Goldschmidt et al. 1985). After the first rainfall (above 20 mm), flowering starts and usually occurs between the months of August and October in southern Brazil (Tubelis 1995).

In contrast to the sub-tropical stimuli, caused by low temperature, in tropical conditions, citrus flowering induction is stimulated by periods of drought. In addition to low temperature, water deficit has also been recognized as another important inductor of flowering in citrus (Cassin et al. 1969). In some regions in the state of São Paulo, where droughts are common during the winter and there is low seasonal thermal variation, the prerequisite to bloom was just rainfall above 20 mm within 5 days after the beginning of July (Reuther 1973; Reuther 1977).

After the flowering date determination, the duration of the flowering period was estimated by the thermal time, represented by degree-days, for all flowering sub-phases, which allowed to identify the dates of the following flowering events: begin, bloom peak, and end of petal fall (Table 3).

Considering the data available (Table 3), after a cumulative rainfall of 20 mm, a total of 96 °C days is required, on average, to start the bloom. Between the start and bloom peak, a total of 147 °C days is required, whereas the sub-period between bloom peak and end of petal fall requires a total of about 229 °C days, being 206 °C days between bloom peak and 50 % of remaining flowers (Fig. 2).

Flowering period for the state of São Paulo

Together with the thermal time required for flowering and its sub-periods, the average temperatures and total rainfall from July to November were used to estimate the probable dates of start, bloom peak, 50 % of remaining flowers, and end of petal fall for the Pera, Natal, and Valencia cultivars, for the period from 1993 to 2013 in 29 locations well distributed throughout the state of São Paulo, Brazil.

Alternation of citrus phenophases in the course of a year proceeds consistently, rhythmically, but their dates differ every year (Table 3). The flowering start ranges in the state, in average, from early August (day 217) to later September (day 262), depending on the climatic

Table 3 Degree-days for the periods between the first 20 mm of accumulated rainfall, occurring in July, and the bloom start (DD rain-start), between the start and the bloom peak (DD start-peak), and between the bloom peak and the end of bloom (DD peak-end), for citrus plants in different experiments and dates of each stage, in the state of São Paulo, Brazil

Year	Location	DD rain-start (°C day)	DD start-peak	DD peak-end	Bloom start Date	Peak bloom Date	Bloom end Date
1999	Itapetininga[a]	59.1	216.5	218.4	18/07	13/08	25/09
2000	Itapetininga[a]	53.4	172.9	202.8	21/08	18/09	14/10
2001	Itapetininga[a]	6.4	240.5	347.6	09/07	20/08	07/10
2002	Itapetininga[a]	97.7	142.5	122.4	14/08	04/09	19/09
2008	Sta. Cruz R. P[b]	131.0	150.8	262.9	27/08	10/09	09/10
2009	Sta. Cruz R. P[b]	147.7	102.5	297.5	13/08	29/08	26/09
2009	Taquarituba[b]	83.3	116.0	129.6	12/08	03/09	20/09
2010	Sta. Cruz R. P[b]	102.5	136.0	244.0	10/10	23/10	13/11
2010	Sta. Cruz R. P[b]	178.0	133.0	289.0	08/08	24/08	19/09
2010	Taquarituba[b]	95.8	60.5	175.2	06/08	25/08	20/09
Average		95.5	147.1	228.9			

[a] Peres et al. (2004)

[b] Silva Júnior (2011)

conditions of the location (Fig. 3). The south of the state has citrus flowering starting earlier than the north part, which is mainly attributed to the rainfall regime in the south of the state, which begins before than in the north.

The climatic conditions have a strong impact on the annual seasonal dynamics of perennial plants (Menzel, 2000). In general, a wide variation in the length of flowering periods among different locations is observed, caused by the temporal and spatial climatic variability observed in southern Brazil. It can be observed in the Figs. 4 and 5, which present, respectively, the average of the total flowering duration, from 29 to 79 days, and the duration between bloom peak and 50 % of remaining flowers, from 14 to 38 days. In these cases, northern São Paulo has shorter flowering durations than southern, which is mainly influenced by the higher temperatures in the north.

In Shiraz and Kerman, Iran, the diurnal and seasonal temperature variability was also described as factors responsible for changes in the flowering dates of citrus (Fitchett et al. 2015). According to these authors, these locations have experienced increases in both maximum and minimum air temperatures associated with earlier citrus bloom peak dates throughout the period between 1960 and 2010.

Based on data from Figs. 4 and 5, temperature can be considered as the most important factor controlling timing, duration, and amount of citrus flowering. An example is when low temperatures in the pre-flowering phase cause a concentrated and late flowering, when the thermal conditions are more suitable for pollination and fruit set (Volpe 1992). But close to the equator, the lack of contrasting seasons causes an ever bearing habit of trees and the combination of high temperatures and humidity plague the citrus industry with a complex disease problem (Reuther 1973), since flowering can occur several times per year.

The lack of thermal seasonality loses its importance under dry conditions since low rainfall during certain periods of the year seems to replace the chilling required to produce a concentrated bloom in citrus plants (Ben Mechlia and Carroll 1989).

According to Ortolani et al. (1991), climatic conditions for the citrus industry in the state of São Paulo, Brazil, allow for the occurrence of up to three blooms per season, which are usually preceded by water deficiency (Ortolani et al. 1991). In general, citrus orchards in the north of the state have a pre-flowering period marked by water deficiency, whereas in the areas located further south, the main environmental factor is the low temperature. In central areas of the state, both drought and/or low temperature can regulate pre-flowering (Ribeiro et al. 2006).

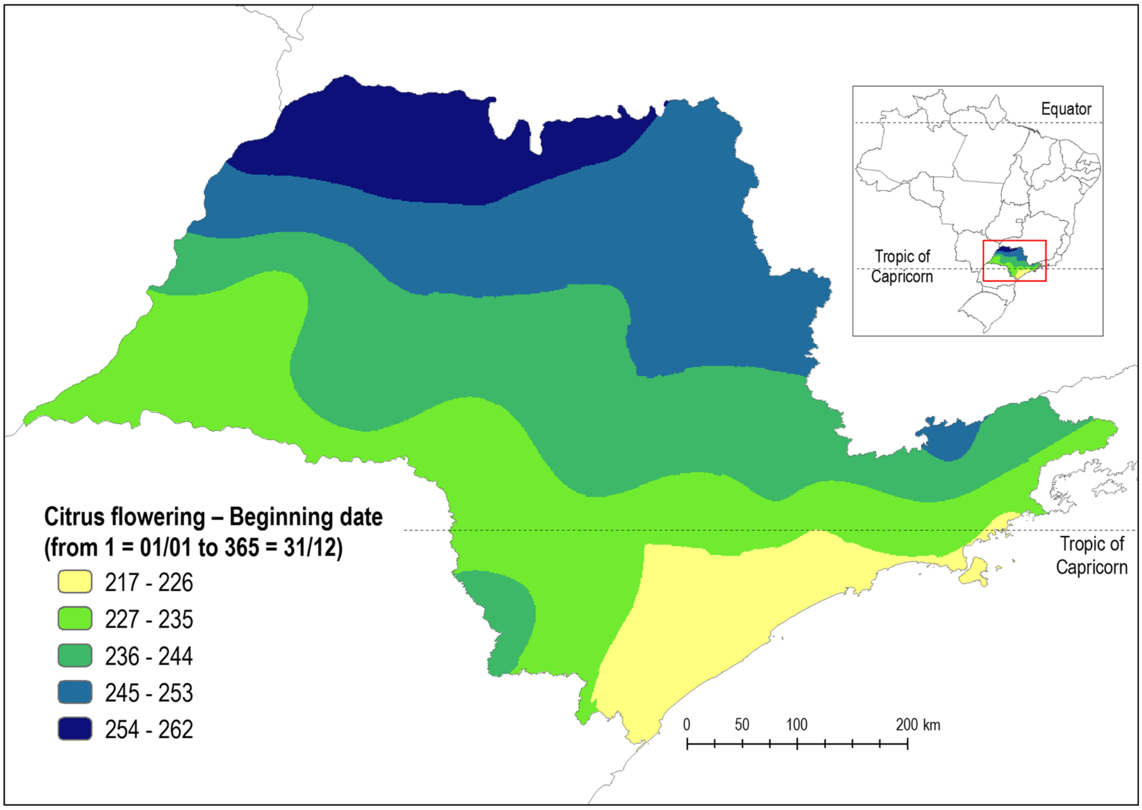

Fig. 3 Average dates of the citrus flowering beginning for the period between 1993 and 2013, in the state of São Paulo, Brazil

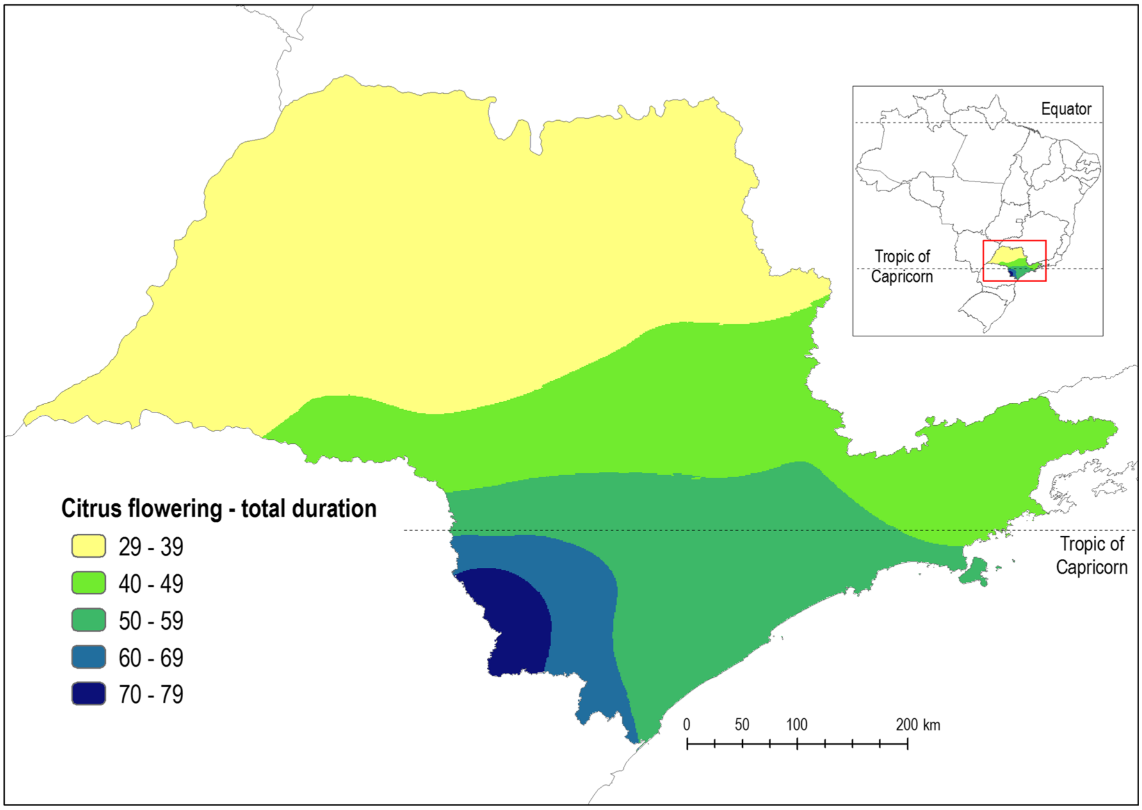

Fig 4 Average citrus flowering duration for the period between 1993 and 2013, in the state of São Paulo, Brazil

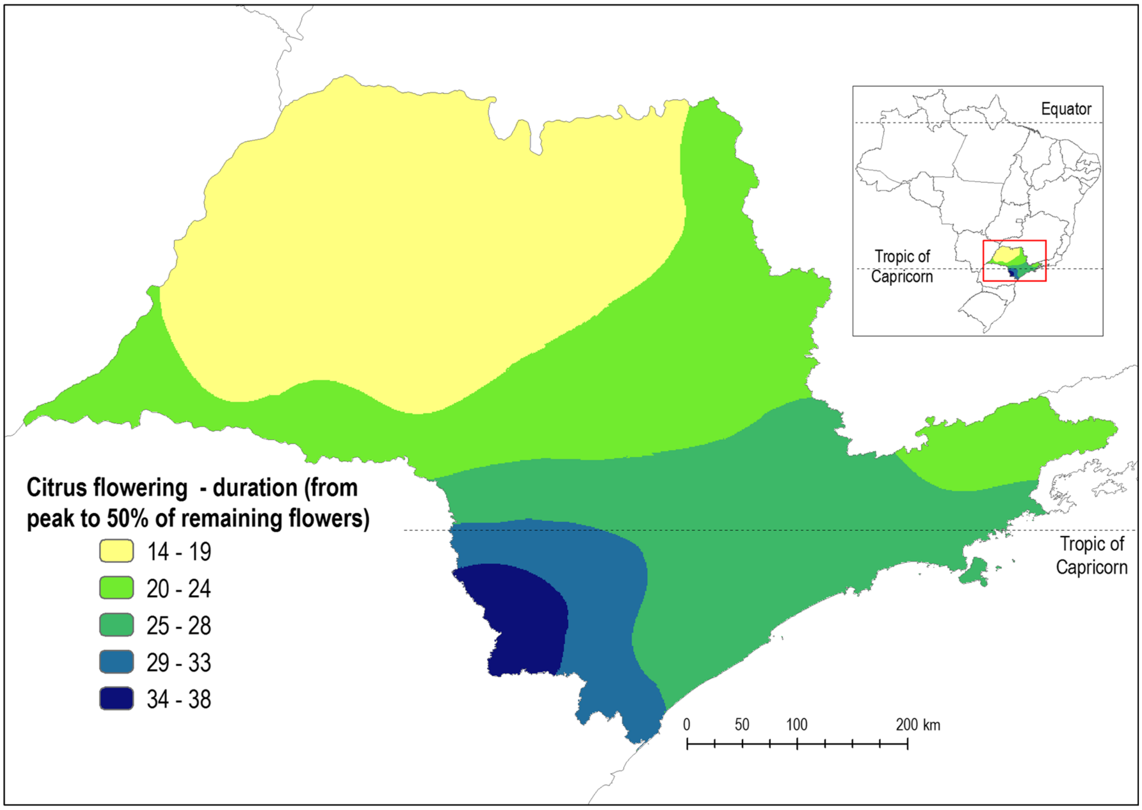

Fig 5 Average duration from the citrus bloom peak to 50 % of remaining flowers for the period between 1993 and 2013, in the state of São Paulo, Brazil

Citrus PFD and accumulated rainfall

PFD incidence values from literature and the respective accumulated rainfall during citrus flowering revealed a definite relationship between the incidence and the total rainfall during the bloom (Table 4 and Fig. 6). Analysis of PFD incidence and total rainfall at different bloom phases showed that the rainfall accumulated between the start and the bloom peak had less influence on the final PFD incidence than the rainfall accumulated between bloom peak and 50 % of remaining flower phases (Table 4), period which requires, on average, 206 °C day (Fig. 2).

Both logistic and Gompertz models explained to a great extent the relationship between PFD incidence and total rainfall; however, the Gompertz model was the one with the best fit when correlating PFD incidence and total rainfall between bloom peak and 50 % of remaining flowers, with R^2 of 0.99 ($p \leq 0.05$) (Fig. 6), and better distributed residues (data not shown). Similarly, Timmer et al. (1994) also found that PFD progress in inoculated young citrus plants was best fit by a Gompertz pattern.

Based on the Gompertz model (Fig. 6), rainfall of 40 mm, between bloom peak and 50 % of remaining flowers, provides up to 10 % PFD incidence, whereas 80 mm can provide up to 60 % of disease incidence, reflecting the typical explosive characteristic of this disease. PFD is sporadic with sudden appearances when there is rain during flowering, since the main ways that PFD spreads is through splashes of rain and by wind (Timmer et al. 1994).

The explosive characteristic of PFD epidemics can be explained by two hypotheses: firstly, by assuming that the inoculum is already present in the area, though the plants will only experience symptoms when climatic conditions become favorable to the dispersal of inoculum from leaves to flowers and to the germination of the fungus; or secondly, by assuming that the initial inoculum would be coming from other plants of the area carried by insects like bees or wind currents associated with rainfall (Peña and Duncan 1989).

PFD causes severe damage even with the use of fungicides in years when rainfall coincides with the flowering period (Porto 1993). Denham and Waller (1981) observed increases in PFD incidence with the reduction of the temperature after the rainfall and prolonged periods of wetting (about 20 h) with at least two consecutive days of rain, regardless of the amount. However, rainfall up to 10 mm with daily leaf wetness duration below 10 h did not promote PFD progress. These authors also mentioned that temperature drop without rainfall did not change PFD incidence, since temperature is a minor climatic variable for this disease, but it is directly associated with the onset and duration of the flowering period, as presented in Figs. 3, 4, and 5.

To prove the feasibility of the Gompertz model adjusted to estimate citrus PFD as a function of rainfall, a validation test was performed with independent data from field experiments in several locations in Florida, USA, and in Estiva Gerbi, São Paulo, Brazil. The results indicated a high and significant degree of proportionality between observed and estimated citrus PFD incidence (Fig. 7), showing that the Gompertz model can be used to predict the PFD with enough precision (R^2=0.79; $p \leq 0.05$) and accuracy (MAE=10.9 %).

PFD occurrence and variability in different locations of the state of São Paulo

PFD incidence was estimated as a function of rainfall between bloom peak and 50 % of the remaining flowers for 29 locations from 1993 to 2013 (Table 2). The results showed high variability of the disease associated with the climatic characteristics of each region (Table 5). Adamantina, Jales, Bebedouro, and Presidente Prudente were the locations with the lowest PFD incidences since the rainfall in these locations during the flowering period is lower than in other regions in the state. Itararé, Capão Bonito, and Ubatuba had the highest PFD incidences.

According to the Köppen climate classification, the state of São Paulo has six distinct climatic types (Alvares et al. 2013b). The type covering the largest area is Cfa. It extends across the entire central part of the plateau and is characterized by highland oceanic climate, with hot summers but with moderate dry season. In this region, where the cities of Botucatu, Assis, Tatuí, and Jundiaí are located, average PFD incidence ranges between 47 and 57 % (Table 5). In the northwest of the

Table 4 Accumulated rainfall recorded from the start to bloom peak (start-peak) and from bloom peak to 50 % remaining flowers (peak-50 %), average temperature, bloom period, and PFD incidence observed in the experiments conducted in Santa Cruz do Rio Pardo, São Paulo, Brazil, from 2008 to 2010 (Silva Júnior et al. 2014)

Year	Rainfall start-peak (mm)	Rainfall peak-50 % (mm)	T_{med} (°C)	Bloom period (days)	PFD incidence (%)
2008	118.0	48.0	22.5	46.0	25.0
2009	304.0	243.0	22.0	50.0	100.0
2009	223.0	160.0	19.0	44.0	100.0
2010	80.0	70.0	24.6	35.0	47.2
2010	10.0	10.0	22.8	55.0	0.0

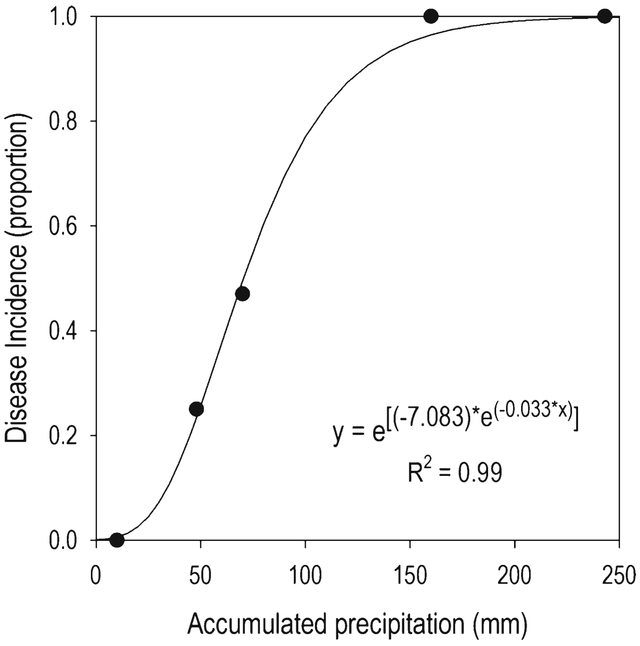

Fig 6 Citrus PFD incidence as a function of total accumulated rainfall between bloom peak and 50 % of remaining flowers. The *points* represent the data observed, and the *line* is the fitted curve, derived from the Gompertz model. Source of observed data: Silva Júnior et al. 2014

state, where the Aw climate predominates (tropical climate with dry winter), the conditions are less favorable to PFD. This region is represented by Jales, Andradina, and Tupã, where the PFD incidence ranges from 20 to 35 %. The locations in the northeast of the state have humid sub-tropical climate, with dry winter and hot summer, classified as Cwa. This region, represented by Ribeirão Preto, Matão, and Limeira, has average PFD incidences ranging from 36 to 40 %. The high-altitude areas, with a humid sub-tropical climate classified as Cfb, are those with the highest average PFD incidence, as observed in Itararé, with 86 % of incidence. Finally, the coastal strip where Af climate occurs, characterized by tropical climate without dry season, average PFD incidence is also high, reaching 51 % in Registro.

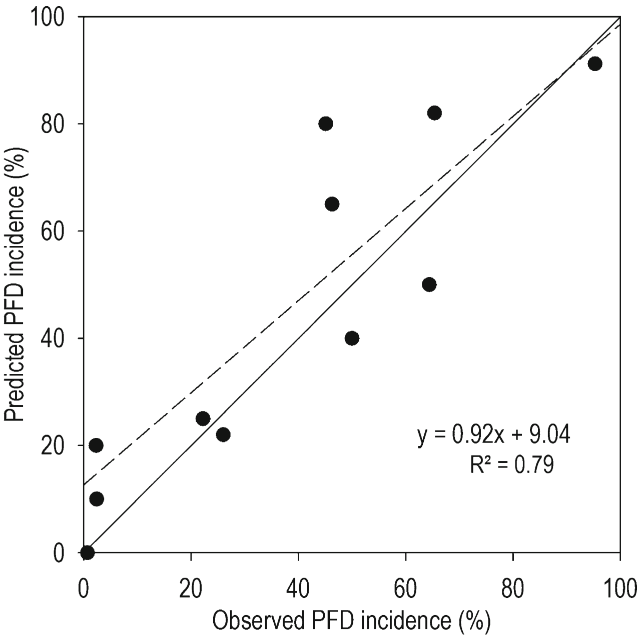

Fig. 7 Relationship between PFD incidences estimated by the Gompertz model and observed in independent field experiments in Florida, USA, and São Paulo, Brazil

Mapping average PFD incidence in the state of São Paulo

Based on the relationship between the PFD incidence estimated by the Gompertz model and the respective latitude, longitude, altitude, and their combinations for the locations selected, a multivariate linear regression model was generated to estimate PFD incidence and represent its spatial distribution in the state of São Paulo, as presented below:

$$\begin{aligned} I_i = {} & 6.52\ 10^3 + 3.17\ 10^2 \times \varphi + 1.04\ 10^2 \times \lambda \\ & + -1.88 \times h + 4.3 \times \varphi \times \lambda + -4.11\ 10^{-2} \times \lambda \\ & \times h + -1.59\ 10^{-2} \times \varphi \times h + 2.06 \times \varphi^2 \\ & + 1.91\ 10^{-4} \times h^2 \end{aligned}$$

where I_i is the estimated PFD incidence for each i pixel of 90×90 m, φ is the latitude in decimal degrees (negative values), λ is the longitude in decimal degrees (negative values), and h is the altitude in meters. This model had a significant R^2 of 0.85 ($p \leq 0.01$) (Fig. 8). By the backward stepwise, the variable square longitude (λ^2) was not significant and, therefore, was excluded from the model.

The map, obtained with I_i estimated for each pixel in the state, shows an increasing trend of PFD incidence from northwest towards the south and the coastal regions, with medium to very high favorability in the central part of the state. The locations with drier climates in the northwest region of the state had lower levels of PFD favorability during flowering (0–30 %). In contrast, locations near and below the Tropic of Capricorn, in the regions with higher rainfall between July and November showed greater favorability for PFD occurrence (>50 %) (Fig. 9).

According to Feichtenberger (1994), in the 1990/91 growing season, yield losses caused by PFD were observed only in the citrus orchards located in Limeira, Campinas, Mogi Guaçu, Araras, and Pirassununga, whereas in 1991/92, 1992/93, and 1993/94, the disease severely affected all main producing regions of the state of São Paulo. In Itapetininga region, located in the southern region of the state, PFD incidence reached 80 % in 1996/97, causing extensive losses

Table 5 Average incidence of PFD estimated by the Gompertz (AI Gomp) and by the linear (AI Num) models for the 40 locations used for model development (D) and test (T) and for simple and cross-validations

Locations	Data	AI Gomp	AI Num	Locations	Data	AI Gomp	AI Num
Adamantina	D	15.7	30.1	Registro	D	51.0	54.0
Andradina	D	35.7	13.5	Ribeirão Preto	D	38.4	27.5
Araçatuba	D	31.7	21.7	Santa C. R. Pardo	D	43.0	45.4
Assis	D	55.2	46.8	São J. R. Preto	D	26.7	27.7
Bauru	D	26.2	37.7	São Paulo	D	50.3	59.8
Bebedouro	D	30.0	27.7	Tatuí	D	47.0	48.7
Botucatu	D	52.3	61.9	Tupã	D	24.8	35.9
Cristais Paulista	D	45.3	16.6	Ubatuba	D	78.1	55.4
Guaíra	D	21.5	22.7	Votuporanga	D	24.3	24.6
Itararé	D	87.0	64.4	Capão Bonito	T	71.4	61.6
Jales	D	19.0	20.4	Itapetininga	T	54.5	56.4
Jundiaí	D	49.2	53.7	Jaú	T	34.1	37.9
Limeira	D	39.7	39.7	José Bonifácio	T	25.9	27.6
Lins	D	34.0	28.7	Pariquera-Açu	T	54.0	51.0
Marília	D	31.0	51.4	São Carlos	T	39.0	51.7
Matão	D	36.6	35.3	Taquarituba	T	60.9	56.0
Mirante do Paranapanema	D	30.2	24.7	Taubaté	T	36.2	46.5
Mococa	D	37.6	27.2	Monte Alegre	T	48.5	45.6
Pindamonhangaba	D	35.3	37.7	Sete Barras	T	47.9	52.7
Presidente Prudente	D	27.4	33.7	Ourinhos	T	52.9	42.1

(Peres 2002). The mentioned areas are located in the southeast and central regions of the state of São Paulo, where, according to the PFD favorability map (Fig. 9), the disease risk is medium-high to high, showing the agreement between the map and field observations.

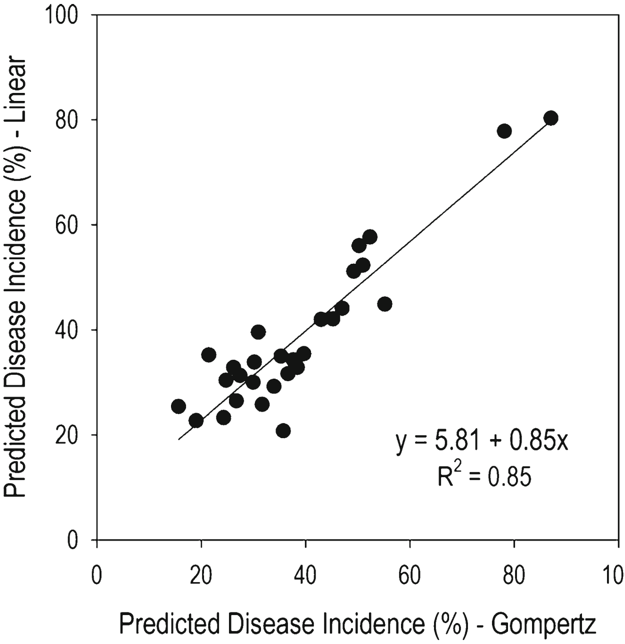

Fig. 8 Relationship between PFD incidence estimated by the Gompertz model and that estimated by multivariate linear regression with integrated variables, for 29 locations in the state of São Paulo, considering the period from 1993 to 2013

Validation of the PFD incidence map

The average PFD incidence obtained for the test locations (Table 5), using the multivariate linear model, had a wide range of variation between 25.9 and 71.4 % when estimated by Gompertz model and between 27.6 and 61.6 % when estimated by the multivariate linear model, consistent with what was observed for the locations used to develop PFD incidence model, between 15.7 and 87.0 % and between 13.5 and 64.4 %, respectively, revealing a slight overestimation of PDF (Fig. 7).

As for the 29 locations previously analyzed, locations in the north of São Paulo, like José Bonifácio, had lower PFD incidence (Gompertz=25.9 % and linear=27.6 %) compared to those locations in the central region, like Jaú, with incidences of 34.1 %, estimated by Gompertz model, and 37.9 %, estimated by the linear model. Locations in the south of the state, such as Capão Bonito, were those with the highest incidences, reaching 71.4 % by the Gompertz and 61.6 % by linear models.

A simple validation of PFD incidence estimated by the multivariate linear model used to generate the favorability map, having as reference the incidence estimated by Gompertz model for the 11 test locations, resulted in a R^2=

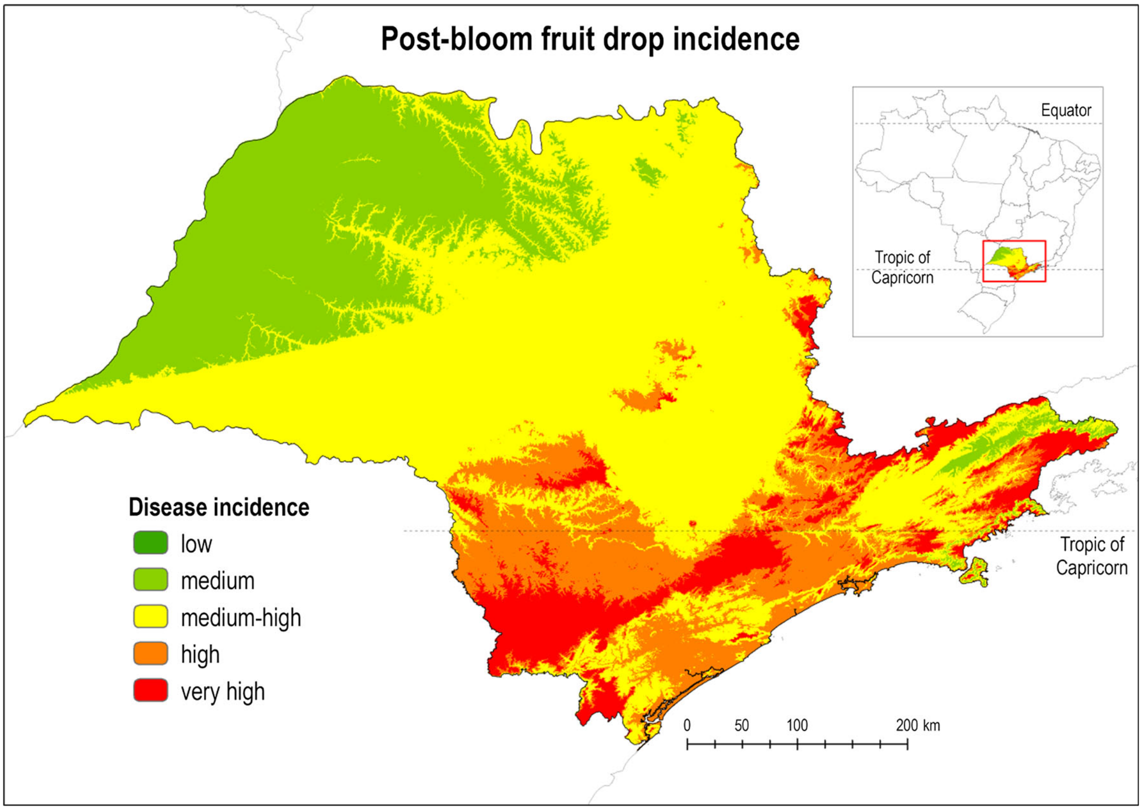

Fig. 9 PFD favorability zones in the state of São Paulo, as a function of climatic conditions

0.81 ($p \leq 0.05$) (Fig. 10a). The index for quality assessment of the model showed that the multivariate linear equation performed well ($P_i=0.71$) for estimating PFD incidence, which is proven also by the mean error (ME=1.39 %), the mean absolute error (MAE=4.75 %), root mean squared error (RMSE=5.63 %), and mean absolute percentage error (MAPE=10.44 %), as well as by a high degree of accuracy ($dr=0.79$) and precision ($r=0.9$).

The cross-validation, using all the 40 locations (Table 5), resulted in a significant R^2 of 0.56 ($p \leq 0.05$) (Fig. 10b). Although the R^2 value was not very high, the proposed multivariate linear model showed to performed well, mainly

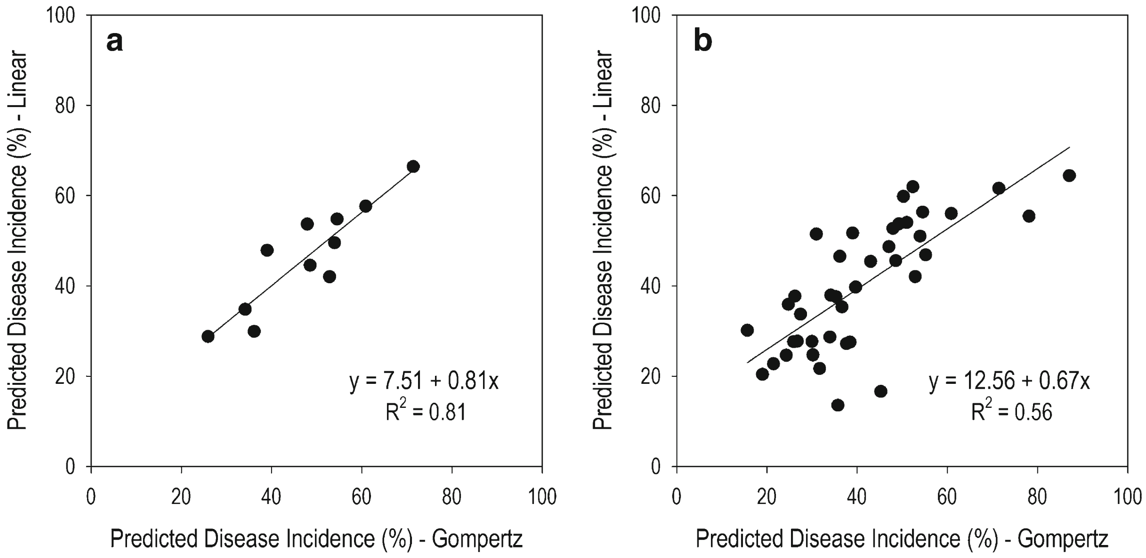

Fig. 10 Relationship between PFD incidence estimated by the Gompertz model as a function of cumulative rainfall during flowering and that estimated by multiple linear regression model with integrated variables, for simple validation of 11 locations (**a**) and for the cross-validation of 40 locations (**b**) in the state of São Paulo, Brazil, for the period from 1993 to 2013

considering the climatic and geographic variabilities of the state of São Paulo. To prove this, other performance indices were calculated, such as the index for quality assessment of the model, which showed that the PFD equation performed well (P_i=0.51), having the following errors: ME=1.13 %, MAE=7.9 %, RMSE=10.6 %, and MAPE=20.8 %, resulting in a reasonable degree of accuracy (dr=0.68) and precision (r=0.75). Although the performance of the multivariate linear model was worse than that obtained by simple validation, it is still considered good enough to represent the PFD incidence variability in the state of São Paulo, once cross-validation is much more rigorous than the simple one.

Conclusions

The citrus flowering beginning is dependent on a combination of low temperatures, accumulated rainfall, and degree-days. The moment when low temperature and cumulative rainfall occur will define the citrus flowering period range. PFD incidence depends on the range of flowering period and the rainfall accumulated between the bloom peak and the 50 % of remaining flowers. According to that, the south and coastal regions of the state of São Paulo are those with the highest PFD favorability, whereas the north and northwestern regions have less climatic favorability. The results of this study allow for the identification of regions in the state of São Paulo where PFD control should be applied more intensively and also the regions where the climatic conditions are considered likely to escape this disease.

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