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Phytophthora infestans Prediction for a Potato Crop

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Abstract The present work studies the seasonal variation of *Phytophthora infestans* concentrations in the atmosphere of a potato crop grown in A Limia. Different models have also been tested to predict the attack of this pathogen in order to establish the necessary treatments. Sampling has been carried out during crop cycles in 2004, 2005 and 2007 by using a volumetric spore trap, located in the centre of the plot at a height of 1.5 m. The collection of meteorological data was done with an automatic gauge. The highest concentrations of *Phytophthora infestans* were registered during June and July, with maximum daily levels ranging from 82 to 145 spores/m^3, as a result of the maximum temperature average, around 16–23°C. Three prediction models for *Phytophthora infestans* have been adjusted to our area of study. The Smith Periods model provides better results in years with low and medium levels of the oomycete inoculum. The NegFRY model is useful to adjust the day of first treatment application, when used together with the Negative Prognosis model. To observe the influence of meteorological parameters on *Phytophthora infestans* spore concentration, besides applying these models, a *Spearman* correlation analysis was carried out. This test allowed the establishment of a correlation between the temperature parameter and the oomycete, obtaining positive and significant correlations ($p<0.01$).

Resumen El presente trabajo estudia la variación temporal de las concentraciones de *Phytophthora infestans* en la atmósfera de un cultivo de patata en A Limia. Se han probado también diferentes modelos para predecir el ataque de este patógeno a fin de establecer los tratamientos necesarios. Se tomaron muestras durante los ciclos de cultivo en 2004, 2005, y 2007 mediante el uso de un captador volumétrico de esporas, ubicada en el centro la finca a una altura de 1.5 metros. Los datos meteorológicos se tomaron con una estación automática. Se registraron las concentraciones más altas de *Phytophthora infestans* durante junio y julio, con niveles diarios máximos fluctuando de 82 a 145 esporas/m^3, como resultado del promedio máximo de temperatura, alrededor de 16–23°C. Se ajustaron tres modelos predictivos para *Phytophthora infestans* en nuestra área de estudio. El modelo de períodos Smith da mejores resultados en años con niveles bajos y medios de inóculo del oomycete. El modelo NegFRY es útil para ajustar el día de la aplicación del primer tratamiento, cuando se usa junto con el modelo de Prognosis Negativa. Además de aplicar estos modelos, se efectuó un análisis de correlación de *Spearman*, para observar la influencia de los parámetros meteorológicos en la concentración de esporas de *Phytophthora infestans.* Esta prueba permitió el establecimiento de una correlación entre la temperatura y el oomycete, obteniéndose correlaciones positivas y significativas ($p<0.01$).

Keywords *Phytophthora infestans* · Meteorological factors · Smith Periods model · Negative Prognosis model · NegFry model

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Translator note: P. infestans is not a fungus. Please check the fourth paragraph (“fungus inoculum”). It should be”oomycete inoculum” (inóculo del oomycete).

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Introduction

The potato (*Solanum tuberosum* L) was introduced in Europe and Asia at the end of the 16th century, becoming from the 19th century one of the most important crops worldwide. It was considered a staple food for low and middle-class families. However, the appearance of an unknown pathogen for the farmers, *Phytophthora infestans* (Mont.) de Bary, caused a great devastation of the crop, with the Irish famine of the 1840 as a consequence. Over one million people died and over 1.5 million people were forced to migrate to other parts of the world (Alexopoulos et al. 1996; Erwin and Ribeiro 1996; Ristaino and Johnston 1999).

The oomycete, *Phytophthora infestans*, which causes the disease of late blight or necrotic tissue, appears especially at high relative humidity and in low-temperature areas, causing the death of leaves, stem and tubers of the plant. It can also completely destroy the cultivation in a short period of time; therefore it is considered the most serious problem for production of Solanaceae crops worldwide (Agrios 1991; Agrios 2002). Due to the aggressive nature of this disease, profit margins are considerably reduced because producers are forced to apply fungicides and to use field resistant varieties (Johnson et al. 1997). In general, *Phytophthora infestans* can develop into late blight at particular temperature ranges and it behaves as a polycyclic disease in the field, originating a disease progress curve which varies with the weather (Harrison 1992).

The design of an effective program to handle a disease requires knowledge of its epidemiology, since understanding the interactions between the pathogen, the host and the environment makes it possible to select the most appropriate techniques to reduce the disease to a point that it does not result in economic losses (Zadoks and Schein 1979; Zwakhuizen et al. 1998). Obtaining reliable predictive models that allow us to know beforehand the atmosphere fungal content in a particular area, and the suitable meteorological conditions for the sporulation of certain types of the pathogen, can lead to forecasting the emergence of fungal blight, thus reducing the use of fungicides (Morales et al. 2004; Naerstad et al. 2007).

In recent years, many studies have been carried out with the aim of identifying both the presence and the dispersion of pathogenic fungal spores in crops (Vittal and Krishnamoorthi 1981; Davies and Main 1986; Rajasab and Chawda 1995; Uddin and Chakraverty 1996; Burt et al. 1998; Albelda 2008) and many authors have developed epidemiological models in order to explain and predict when the disease starts with the aim of determining the appropriate timing for initiation of control measures. (Bruhn and Fry 1981; Shtienberg et al. 1989; Wiik 2002; Bugiani et al. 1996; Fry 1998; Díaz et al. 1998; Johnson et al. 1998; Gudmestad 2003). Almost all of these models are based on the use of meteorological parameters, especially relative humidity, temperature and precipitation.

Material and Methods

A Limia is located in the centre of the province of Ourense with an average altitude of 640 m above sea level. It is one of the most well-defined territorial units of Galicia, since it is basically formed by a depression filled up with sediments whose central part was occupied in the past by lake Antela. This lake, which has been recently drained, is now intensively cultivated. The hydrographical network was formerly delimited by lake Antela and, after being drained, the network was organized around river Limia, which slopes the town downward, making drainage difficult. The phreatic level, near the floor level, is controlled by channels and floodgates. Irrigation is used in almost the entire cultivated area.

Due to its location and altitude, the weather in A Limia presents a combination of both oceanic and Mediterranean characteristics, with a tendency to continental weather. The oceanic features are represented by the rainfall (from 867 mm to 1,237 mm yearly) and its mild temperature in winter. The Mediterranean features are represented by droughts in summer (from 126 mm to 146 mm) and finally, the continental weather is manifested by the high average temperature (between 13°C and 13.7°C), according to data obtained as a normalized average.

The annual distribution of rain shows a contrast between the rainiest months (December and January, between 130.6 mm and 112.2 mm monthly) and the dry season, in July and August (between 18.5 mm and 25.6 mm monthly). Based on summer and winter classification, as well as humidity levels, and taking into account the normal thermopluviometric data, Xinzo de Limia presents a warm and fresh Mediterranean weather (Carballeira et al. 1983).

The main crop in the A Limia region is the potato, with an average production of 5 million kilos per year, under the protected geographical indication (PGI) *Pataca de Galicia* (Galician potato), label which has been recognised by the European Community. This recognition corresponds to four different areas of production: Bergantiños (A Coruña), Villalba (Lugo), Lemos (Lugo) and A Limia (Ourense).

Half of the overall production of potato is intended for the Galician market and it belongs to the Kennebec variety.

The study was conducted during 2004, 2005 and 2007 and was continuously monitored from April 20th to September 15th in those years. Monitoring was carried out by using a volumetric VPPS 2000 pollen-spore trap, now manufactured by Lanzoni (Hirst 1952), and located in

Damil, in the A Limia region. The Lanzoni sampler is calibrated to handle a flow of 8 l of air per minute. Spores impact on a cylindrical drum covered by a melinex film, coated with a 2% silicon solution as trapping surface. The drum was changed weekly and the exposed tape was cut into seven pieces, which were mounted on separate glass slides. Spore identification was performed by using a Nikon Optiphot II microscope equipped with a 40×/0.95 lens. Spore counting was done by using the model proposed by the R.E.A. (*Spanish Aerobiology Network*), consisting of four continuous longitudinal traverses along a 24 h slide (Domínguez et al. 1992). Concentrations of the fungal type under study are expressed in spores per m^{-3} of air.

Meteorological data was obtained by using a meteorological *HOBO Pro Series. temp. RH (°C) 1998 ONSET*, which showed temperature and relative humidity data every hour during the entire period of study. Rainfall data was extracted from the *Areeiro Estación Fitopatológica* website, which has a weather station available in the A Limia district. The weather station is located 3,000 m from the potato crop.

The models tested, as described below, allow the prediction of sporulation of *Phytophthora infestans* conidia, and allow the adjustment for the application of the first phytosanitary treatment for the crop in order to prevent the development of the late blight disease.

The predictive models for late blight used for the three crop cycles (April–September) are the following:

Smith Periods Model Minimum temperature and relative humidity are taken into account in this model. The authors of this model establish the periods according to the aforementioned parameters, considering that a Smith period occurs when minimum temperature is higher than 10°C and relative humidity is higher than 90% for 11 h, for two consecutive days. If the criteria for temperature and humidity come true in the first day, and the second day reaches 10 h of relative humidity higher than 90%, this indicates that only one Smith period has taken place (Smith 1956; Hims et al. 1995).

Negative Prognosis Model This model was developed by Ullrich and Schrodter (1966). The authors take into account relative humidity or precipitation and the average temperature within the field of the crop. It is an accumulative model, because it determines the periods when attacks of the pathogen on the potato crop are very unlikely to occur. Disease is expected to happen when the accumulated risk value exceeds the 150 threshold. This threshold must be adjusted to local conditions.

The values of the coefficient r of this model are established according to Table 1, which separates temperature levels corresponding to the consecutive hours with relative humidity higher or equal to 90% or lower than 70%. Rainfall values higher or equal to 0.1 mm/h can be counted.

NegFRY Model This model (Fry et al. 1983) takes into account the effect of meteorological conditions and also the effect of cultivar resistance; in this case Kennebec is considered a sensitive variety.

Our model used jointly the model of Negative Prognosis to determine the disease risk and the model of NegFry for fungicidal applications.

This model established the average temperature in terms of different ranges (<3°C; 3–7°C; 8–12°C ;13–22°C; 23–27°C and >27°C) within each range the hours of relative humidity higher or equal to 90% were to be counted and, according to the number of consecutive hours, a value of risk units established in Table 2 is bestowed. The said units are cumulative.

To verify whether there is a relation between the concentrations of oomycete spores and weather variation, a linear correlation analysis was carried out, taking the quantity of spores as a dependent variable and temperature, humidity and rainfall as independent variables.

Bearing in mind that spores do not follow normal distribution models, the linear correlation coefficient was calculated with the Spearman's linear correlation test. It is a nonparametric statististical test that we have used in this case due to the lack of normality in the data. A correlation test was performed to find a possible correlation between

Table 1 Risk value of coefficient r for the Negative Prognosis model (Excerpted from Ullrich and Schrodter 1966)

Multiplication factor (r)	Number of hours temperature (°C) averages are in this ranges (h), or other conditions to be met	RH or Precipitation requirements, or other conditions to be met
0.899	10.0–11.9	4 or more consecutive hours at RH≥90% or rain≥0.1 mm/h
0.4118	14.0–15.9	
0.5336	16.0–17.9	
0.8816	18.0–19.9	
1.0498	20.0–21.9	
0.5858	22.0–23.9	
0.3924	10.0–11.9	10 or more consecutive hours at RH≥90% or rain≥0.1 mm/h
0.0702	14.0–15.9	
0.1278	16.0–17.9	
0.9108	18.0–19.9	
1.4706	20.0–21.9	
0.855	22.0–23.9	
0.1639	15.0–19.9	Do not consider RH or rain. add 7.5479 to the product r × h
0.0468	Number of hours with average RH<70%	Subtract 7.8624 from the product r × h

Table 2 Value of risk units determined by temperature and periods of high relative humidity for NegFRY model (Excerpted from Fry et al. 1983)

Average temperature °C	Consecutive hours of relative humidity≥90% that should result in blight units of:							
	0	1	2	3	4	5	6	7
>27°C	24							
23–27°C	6	7–9	10–12	13–15	16–18	19–24		
13–22°C	6					7–9	10–12	13–24
8–12°C	6	7	8–9	10	11–12	13–15	16–24	
3–7°C	9	10–12	13–15	16–18	19–24			
<3	24							

daily mean airborne conidial number and the main meteorological factors: rainfall (mm), relative humidity (%) and maximum, minimum and average temperatures (°C). A significance degree for the confidence intervals of 95% (*) and 99 %(**) was calculated. The statistical program applied was SPSS16.

Results

During the 3 years of the study the highest daily average of *Phytophthora infestans* concentrations were recorded in the first phenological phases of the crop with a reduction as the crop cycle progressed (Fig. 1).

In the 2007 cycle, a total of 2,660 spores were counted, in comparison with 1,706 and 1,157 spores in 2004 and 2005, respectively. The evolution during the three cycles shows that the most important oomycete concentrations were registered from the middle of June to the end of July, with the maximum concentrations occurring during this period, as a response to the maximum temperature average of 16–23°C. These intervals are adequate for conidia production.

During the 2005 cycle, the maximum value was recorded on 3rd June, with 145 spores/m^3 followed by the 2007 cycle, with 131 spores/m^3 on 31st May and finally, 82 spores/m^3 on 5th June 2004. During this period, plants were developing their leaves and lateral shoots, meaning that plants were in a supersensitive phenological phase and therefore, were very sensitive to pathogen attack.

After the application of the tested models as described, and in order to predict a possible attack of oomycete spores, we observed that (Fig. 2):

Smith Periods Model On 10th July 2004, the first Smith period occurred at 100%, preceded by one Smith period at 90%, on 6th July. During the 2005 crop cycle, the first Smith period occurred on 19th June, at 100%, preceded by a period at 90% on 15th June, as against 2007 cycle, when only one Smith period occurred on 29th August (Table 3).

Negative Prognosis Model After calculating the negative prognosis of the three cycles under study, the minor number of accumulated values was produced during the 2007 cycle, with a total of 178 units used for the present study. In the 2004 and 2005 cycles, the total accumulated units were 275 and 391, respectively. This shows that a higher risk of infection occurred in 2007.

Ullrich and Schrodter (1966) suggest 150 accumulated units for predicting the moment when the first treatment must be done in their area of study. In our area, this threshold was obtained on 29th July (2004 year cycle), 4th July (2005 year cycle) and 16th August (2007 year cycle). This is insufficient to predict the first treatment time. We must reduce accumulative units to a threshold that protects initial concentrations of the potato crop.

By using the NegFry model, 30 accumulative units are required for the application of the first treatment. This value was obtained in the 2004 year cycle on 8th June. During the 2005 year cycle this value was reached on 4th May and, finally, in the 2007 year cycle on 27th May.

The results obtained by using the Spearman's correlation test lead us to the following conclusion: daily spores concentrations of *Phytophthora infestans* during the 2004 cycle show a weak positive correlation of 0.411 ($p<0.01$) taking into account average temperature parameter and a weak negative correlation of -0.337 and -0.245 ($p<0.01$) by applying average relative humidity and rainfall parameters, respectively. Nevertheless, correlations for the 2005 and 2007 cycles show no statistical significance (Table 4).

Considering the years of sampling, a weak positive correlation of 0.134 ($p<0.01$) with the minimum temperature and a weak negative correlation of -0.130 ($p<0.01$) with the average relative humidity were found.

Discussion

Some authors confirm the importance of climate during a crop's production cycle to prevent the development of plant diseases (De-Wei and Bryce 1995; Ricci et al. 1995; Flores 2006). It

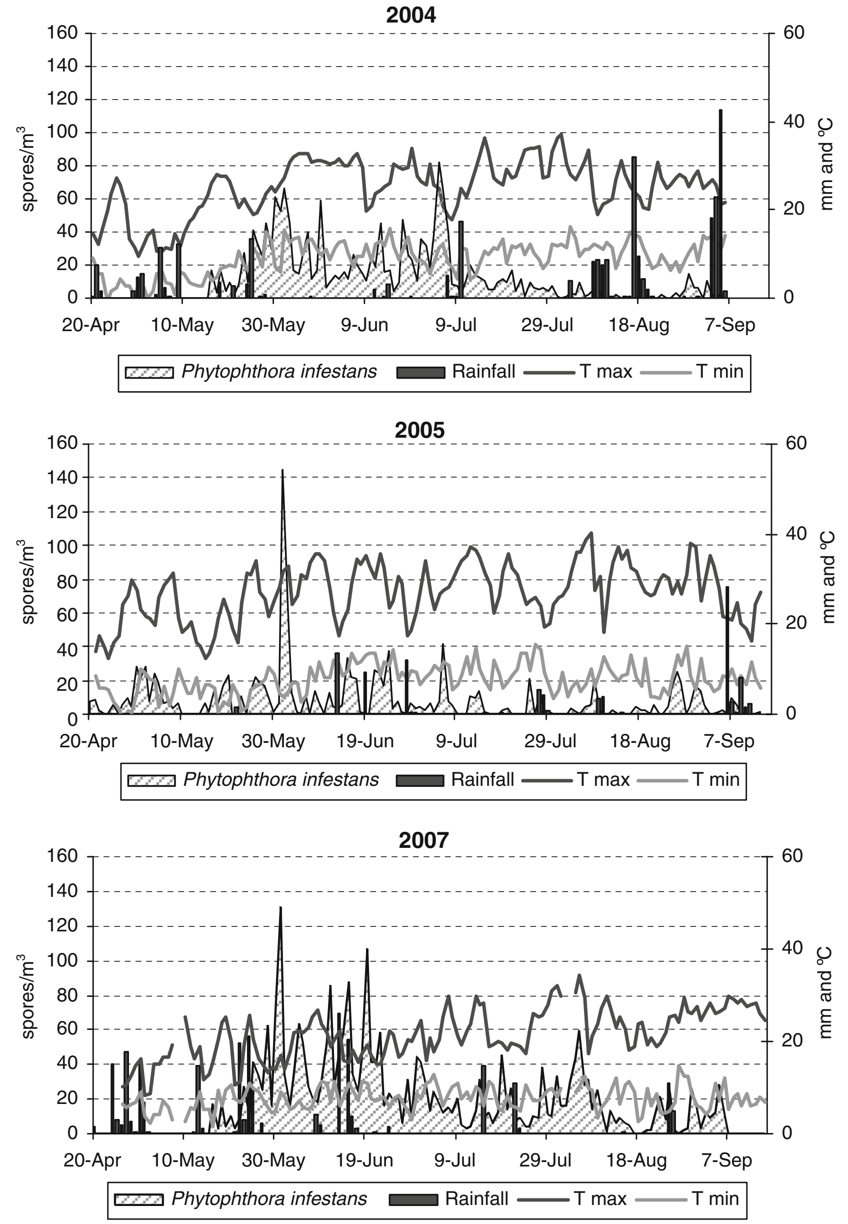


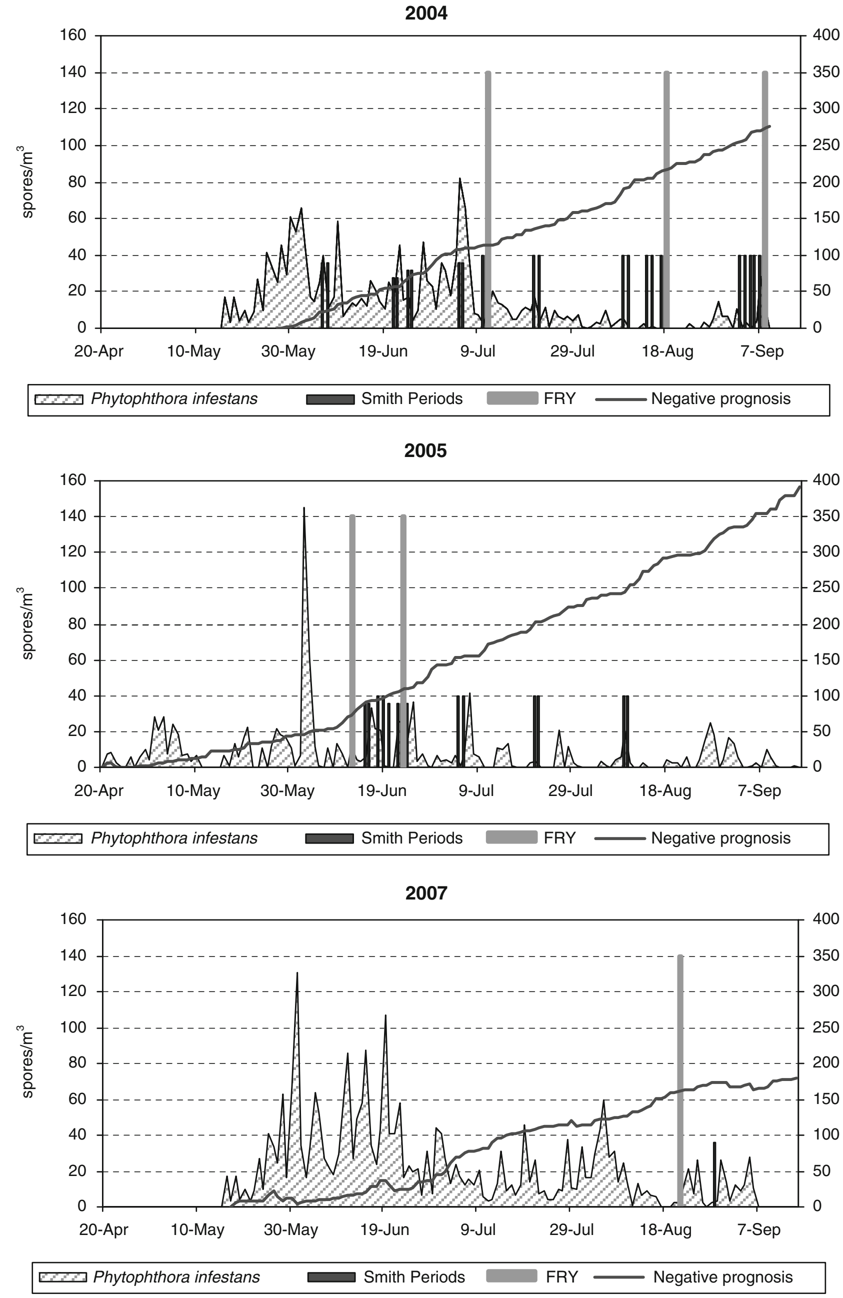
Fig. 1 *Phytophthora infestans* evolution with each crop cycle's meteorological conditions

has been observed that *Phytophthora infestans* spores are present in the atmosphere of the area under study during most parts of the crop cycle,with some differences reported due to weather variability. The first 2 years presented dry and warm summers, whereas in 2007 temperatures were below normal and it was a high rainfall year. Weather parameters such as temperature, rainfall and relative humidity have directly influenced the development of mildew disease (Coscollá 1980; Escalante and Farrera 2004). The results of the present study show that a minimum temperature and relative humidity are the meteorological parameters that have a stronger influence in the development of *Phytophthora infestans* spores. The optimal temperature for oomycete formation is 21°C, but spores are able to stay alive at temperatures ranging from 0°C to 28°C. Humidity should be higher than 95% for sporangia formation and less than 8 h of high relative humidity are needed in order to produce zoospores under favourable temperature conditions (Fernández 1994).

In order to avoid losses in potato yield, growers should adjust the first day of fungicide treatment to control the disease throughout the entire crop cycle (Campbell and Madden 1990; Shtienberg and Fry 1990). Therefore, several authors (Raposo et al. 1993; Hansen et al. 1995; Hardwick 1998; Johnson et al. 1998; Howard and Schawartz 2003; Batista et al. 2006) are testing and analyzing different models, trying to adjust the first day of the treatment according to meteorological parameters.

The Smith Periods model was originally developed as an indicator of overall deterioration risk across a wide

Fig. 2 Results of prediction models for *Phytophthora infestans* during the three year's crop cycles



geographical area of the United Kingdom (Hims et al. 1995; Barrie and Bradshaw 2001). It is a model that measures the risk of mildew outbreak. However, it is important to note that the occurrence of a Smith Period does not necessarily lead to the application of a fungicide spray over the crops (Bradshaw et al. 2000).

The Smith Periods model is indicated for areas and years with low or medium inoculum pressure (Smith 1956). This

Table 3 Results for the application of the first treatment with of the Smith Periods model (100%). Negative Prognosis model (100 accumulated units), and NegFry model (30 accumulated units)

	Total *Phytophthora infestans* spores	Smith periods (100%)	Negative prognosis (100ud acum)	FRY (30uds acum)	First treatment (days)
2004	1706	10 July	2 July	8 June	8 June–11 July
2005	1157	19 June	20 June	4 May	4 May–20 June
2007	2660	29 August	16 July	27 May	27 May–29 August

Table 4 Correlation Spearman coefficients ($^{**}p<0.01$; $^{*}p<0.05$) between spore concentrations and meteorological parameters

	Phytophthora infestans							
	2004		2005		2007		2004–2007	
	N=142		N=147		N=115		N=404	
	r	p	r	p	r	p	r	p
Mean T	**0.411****	0.000	−0.092	0.129	−0.142	0.129	0.007	0.886
Maximum T	**0.364****	0.000	−0.086	0.051	−0.183	0.051	−0.053	0.287
Minimum T	**0.324****	0.000	0.033	0.999	0.000	0.999	**0.134****	0.007
Mean RH	**−0.337****	0.000	0.095	0.659	0.042	0.659	**−0.130****	0.009
Rainfall	**−0.245****	0.003	0.095	0.498	0.064	0.498	−0.050	0.316

could be the reason why in 2007, for the area under study, only one Smith Period was calculated in the final stage of the crop, which was insufficient to measure the risk of infection since levels of *Phytophthora infestans* were high from May. This fact has been also reported by Henshall and Beresford for two different locations (2004).

After the analysis of oomycete levels in the atmosphere of the crop (Fig. 1), it is clear that high concentrations of this pathogen have been detected in the crop before each risk period described by the Smith Periods model, Negative Prognosis model or NegFry model. Therefore, it is necessary to modify and adjust these models to our weather conditions, taking into account that A Limia is an area with high humidity levels.

The data presented in the results section for potato late blight follow the exact pattern that has been proposed for particular areas of Denmark, Norway and Sweden (Fry et al. 1983; Bruhn and Fry 1981) when using the NegFry model. The same can be applied to a particular location of Germany (Ullrich and Schrodter 1966) by using the Negative Prognosis model while the same occurs in several areas of England and Wales (Hims et al. 1995) by applying the Smith Periods model. These models were adapted to our weather conditions in order to predict the occurrence of this pathogen in the crop areas and set the first day of treatment to control the disease.

To set the timing for pathogen spread by using the Smith Periods model, we must reduce relative humidity requirements to at least 7 consecutive hours, with a relative humidity equal to or higher than 90%. If this occurs during two consecutive days and the minimum temperature is higher than 10°C, we can predict pathogen sporulation in the early stages of the A Limia potato crop.

The same happens with the Negative Prognosis model. In order to predict the first day of treatment with fungicides we have reduced the accumulated units value to 10. After developing these changes, during the 2004 cycle we observed one Smith period on 28th May, with more than 30 accumulated FRY units and Negative Prognosis values over ten accumulated units on 8th June (Table 5). Therefore, for this potato crop cycle, the first treatment should be applied between 28th May and 8th June. In the 2005 potato crop cycle we observed the first Smith period on 10th May and 30 accumulated FRY units on 4th May. The Negative Prognosis value was higher than ten accumulated units on 13rd May. Consequently, the first treatment for 2005 potato crop cycle should be applied between 4th and 13rd May.

Finally, in the 2007 potato crop cycle the first treatment should be applied between 26th May and 8th June, according to 8th June Smith period, Negative Prognosis accumulated value higher than ten units on 26th May and accumulated FRY units over 30 on 27th May.

The first day of treatment with fungicides depends on the precipitation, since this can reduce the effectiveness of the fungicide treatment by exercising a washing effect and making it necessary to repeat the treatment.

Finally, the results obtained by using these correlations have shown similar patterns to those which have been previously found by other authors corresponding to other conidial types in areas with weather conditions similar to the A Limia region (Ballero et al. 1992; Díaz et al. 1996; Herrero et al. 1996; Paredes et al. 1997; Méndez et al. 2000; Sabariego et al. 2000;

Table 5 Results for the application of the first treatment by adjusting the threshold for the Smith Periods model, Negative Prognosis model and NegFry model to the A Limia region

Adjustment model for A Limia				
	Smith Periods	Negative prognosis (10ud acum)	FRY (30uds acum)	First treatment (days)
2004	28 May	8 June	8 June	28 May–8 June
2005	10 May	13 May	4 May	4 May–13 May
2007	8 June	26 May	27 May	26 May–8 June

Troutt and Levetin 2001; Aira et al. 2003; Morales et al. 2004; Rodriguez-Rajo et al. 2005).

Therefore, the different models have been adapted to the A Limia area in order to predict *Phytophthora infestans* spread in the potato crop (Smith Periods model) and to set the first day of treatment with fungicides (Negative Prognosis model coupled with NegFRY model) to control late blight. We have considered a Smith period to have occurred if the following conditions come true: relative humidity equal to or higher than 90% for at least 7 consecutive hours, with a minimum temperature of 10°C for two consecutive days. It is recommended that the first application of a fungicide should occur when 30 accumulated FRY units and 10 Negative Prognosis accumulated units takes place.

The aerobiological study of potato crops and the use of these prediction models duly adapted to a geographic area's weather conditions are useful to predict the timing of the initial application of a fungicide treatment. However, variability in each year's weather conditions makes it necessary to extend this study for several years.

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