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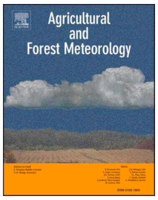

Looking for a sustainable potato crop. Field assessment of early blight management

Laura Meno, Olga Escuredo [*], M. Shantal Rodríguez-Flores, M. Carmen Seijo

Department of Vegetal Biology and Soil Sciences, Faculty of Sciences, University of Vigo, As Lagoas, 32004, Ourense, Spain

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ABSTRACT

Potato crops are susceptible to numerous field diseases causing significant losses in the quality and tuber yield. Control measures have a negative impact in soil and water resources affecting also farmers' health and food security. Hence, a more sustainable agriculture management is a need to preserve ecosystems. Therefore, the objective of this study was to evaluate the response of nine potato cultivars (Fleur Bleue, Frisia, Fontane, Louisa, Agria, Daifla, Red Pontiac, Kennebec and Desiree) against early blight using a Decision Support Systems (DSS) in a potato-producing area from Northwest Spain. The experimental design was established using control plots and sprayed plots with fungicide according to a disease risk model adapted to the geographical region (DSS plots). Disease rating and severity were evaluated in field from the appearance of the first symptoms to final of senescence and the area under disease progress curve (AUDPC and r-AUDPC) was calculated. Aerobiological monitoring of main *Alternaria* species responsible potato early blight (*Alternaria solani* and *Alternaria alternata*) and the most vulnerable phenological stages were also considered. The susceptibility of the potato cultivars was analyzed based on the weather, severity of the disease and tuber yields. Specifically, temperature and leaf wetness were the meteorological variables that most influenced on the concentration of *Alternaria*. Conidia accounted for the previous week was the variable that most influenced in development of symptoms measured by AUDPC in natural conditions. Yields in the cultivars of DSS plots were higher than in control plots. Therefore, alternative pest management strategies, and specifically, Decision Support Systems for pest assessment are crucial for sustainable potato production. In this sense, the integration of particular information on disease resistance of commercial cultivars, phenological development of plant, or fungal particles surrounding the crop atmosphere could support these systems for better adjustment without compromising tuber yield and environment.

1. Introduction

Since the middle of the last century, the conventional agricultural systems has been changed by introduction of new mechanized techniques and intensive agricultural systems. This new trend of producing food was based on the adoption of modern agricultural practices and technologies, which made it possible to achieve high production yields. The intensification of agricultural production has been necessary to supply food demanded by demographic growth. In Europe, the yield of potato crop has increased by 190% since the sixties (FAO, 2020). In addition to the use of fertilizers, resistant cultivars and the specialization of agricultural equipment, the increased use of pesticides to minimize pest damage have contributed positively to crop yields (Warren, 1998; Webster et al., 1999; Veitía et al., 2014; Damos, 2015; Xue et al., 2019). However, mechanisms for plant protection are changing in reaction to the societal needs, looking for integrated pest management (Damos, 2015).

Potato plants are susceptible to a wide variety of diseases that severely can reduce yield, quality and storability of tubers (Singh et al., 2015; Landschoot et al., 2017). Some researchers reported a decrease in the annual yield of up to 30% due to fungal diseases, bacteria or insects (Shtienberg et al., 1990). Early blight caused by *Alternaria* species, mainly *A. solani* (Soraeur) and *A. alternata* (Fr.) Keissl, is one of the common diseases in potato crop (Van der Waals et al., 2001; Horsfield et al., 2010; Abuley and Nielsen, 2017; Meno et al., 2020). The disease can occur over a wide range of climatic conditions and can be very destructive if it is left uncontrolled (Van der Waals et al., 2001; Singh et al., 2015; Escuredo et al., 2019a; Campos and Ortiz, 2020). Due to the

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[*] Corresponding author.
E-mail address: oescuredo@uvigo.es (O. Escuredo).

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ability of *Alternaria* spp. to survive high temperatures, early blight is likely to be more aggressive in the coming decades in Europe and potato production areas (Kasprzyk et al., 2015; Runno-Paurson et al., 2015; Skjøth et al., 2016; Escuredo et al., 2019a). Therefore, studies based on the behavior of such aggressive diseases in the field could be useful for planning agricultural practices and adjust fungicide treatments.

Early blight is a polycyclic disease, and outbreaks can accumulate rapidly if environmental conditions are favorable. *Alternaria* survives as spores and mycelium in infected plant and in plant residues. Alternative hosts like eggplant and several solanaceous weeds including black nightshade (*Solanum ptycanthum*) and hairy nightshade (*Solanum physalifolium*) are factors favoring disease development, but also cultivar resistance and maturity of tubers (Abbas et al., 1998; Vloutoglou and Kalogerakis, 2000; Olanya et al., 2009; Singh et al., 2015). The symptoms on leaves readily recognized by its distinctive bull's-eye-shaped lesions (approximately 3 to 12 mm of diameter) restricted within leaf veins. The area under the disease progress curve (AUDPC) has been used to assess severity of disease in the field, expressing the dynamics of the epidemic during the crop season (Shaner and Finney, 1977). The characterization of cultivars based on the resistance level using the disease severity integrated over time as AUDPC improves the interpretation of the response of epidemiological symptoms in the field (Veitía et al., 2014).

Considering the use of potatoes as human food for growing population and the importance of more environmentally friendly agriculture, alternative pest management strategies and integrated pest management programs including Decision Support Systems (DSS) are crucial for sustainable potato production. However, in practice, successful decision-making is preceded by the availability of integrated and high-quality information (Damos, 2015). Improvements in the disease management programs are dependent on comparative epidemiology and interrelationships among climatic conditions and the components of epidemic systems (Naseri and Sharifi, 2019). Prediction models based on meteorological variables are an opportunity for the environmentally friendly application of chemical products. The most widely used DSS for potato early blight control were TOMCAST (Madden et al., 1978; Abuley and Nielsen, 2017; Meno et al., 2020), interrupted wet periods (IWP) (Van der Waals et al., 2003; Meno et al., 2019), and PLANT-PLUS (Landschoot et al., 2017). The adaptation of these systems based on the climatic conditions of the specific geographic area is essential for the success of disease control in the field.

However, the precise modelling of plant disease is difficult because it requires specialists to identify critical biophysical processes driving disease spread based on time and geographical area (Pan et al., 2010). In this sense, aerobiological sampling allows the identification of pathogens in the environment of potato plants, relating it to the particularities of the cultivated area. This information combined with meteorological parameters and epidemiological events makes it possible to design and to apply a more accurate risk prediction model.

Dealing with the strategy of the European Union to reduce the use of pesticides enhancing food security and environmental quality, this study looks after a more sustainable agriculture in potato crop. The application of DSS for pest control, reducing pesticide sprays, has demonstrated good results (Abuley et al., 2017; Meno et al., 2019; 2020), allowing the preservation of rural environments, water resources and the ecological communities that inhabit them. This is relevant for A Limia region (Northwest Spain), which is a special protection area for nature included in the Habitat Directive (Council Directive 92/43/EEC). Therefore, the present study focused on the analysis of the efficacy of TOMCAST model to control early blight in potato fields from Northwest Spain. The progress of the disease in nine cultivars was evaluated, monitoring symptomatology in the field and *Alternaria* conidia levels in the plant environment. Finally, susceptibility of the potato cultivars was considered by measuring severity of the damages and yields.

2. Material and methods

2.1. Experimental site and design

Field experiments were carried out in Betán, Baños de Molgas (Ourense, Northwest Spain), 42° 14′ N, 7° 43′ W, during 2020 potato growing season. The growing period was from April to September when potatoes were harvested. For the study, eighteen experimental plots of 18 m^2 (1.5 m x 12 m) were established, leaving 1 m separation between plots to avoid leaf contact. Nine certified potato cultivars were sowed for the experiment according to fresh-market and industry preferences: Desiree (DE), Frisia (FR), Fontane (FO), Louisa (LO), Agria (AG), Daifla (DA), Red Pontiac (RP), Kennebec (KE) and Fleur Bleue (FB). The potato cultivars were planted in duplicate plots (control plot and DSS plot). DSS plots were used to test early blight model applying fungicides when necessary and the control plots was used as a control (without fungicide applications).

All the potato cultivars are for fresh consumption, although some are also destined for industrial processing like frying process (Agria, Fontane, Louisa and Fleur Bleue). Regarding maturity, the earliest were Frisia and Daifla, with medium maturity Kennebec, Fontane, Red Pontiac and with late maturity Desiree, Agria and Louisa. Two weeks before sowing, fertilization and weed control measures were applied according to farmeŕs standard practices. A total of 15 m^3/ha of composted cattle manure and chemical synthesis fertilizer N-P-K in proportion 9-18-27 at 500 kg/ha were applied. The study was carried out without irrigation technique.

2.2. Plant phenology development monitoring

The monitoring of phenological stages were from sowing date on April, 11th to last day of senescence of late cultivars, on July, the 31st. In the present study, the main phenological phases of the crop were considered to relate it to the most susceptible phase for the disease. For this, BBCH scale of Hack et al. (1993) was followed. The emergence (E) included the E0 of BBCH scale; foliar development (FD) was from E1 to E3 (when 80% of plants were in 309 of BBCH scale). The maturation (M) considered between end of foliar development phase and beginning of senescence (when 25% of plants start to dry out and turn yellow) and senescence (S) included E9 phase of BBCH scale. Thus, the analyzed phenological phases were summarized in four: emergence (E), foliar development (FD), maturity (M) and senescence (S).

2.3. Weather monitoring

The meteorological parameters (temperature, relative humidity and leaf wetness periods) were recorded by using a portable weather station iMETOS ® 3.3. (Pessl Instruments, Weiz, Austria) placed at 1.5 m height inside the study field. The records were extracted per hour. The rain data were obtained from the National Weather Service website (National Weather Service Website) positioned 5 km from study plot.

2.4. Disease severity assessment

Severity was measured following the description of Rahmatzai et al. (2017) with some adaptation (Table 1). In each plot, three potato plants were marked to monitor early blight disease severity progression (six plants per cultivar). It was evaluated from sowing date to senescence (Table 1).

The disease severity data was used to calculate the area under the disease progress curve (AUDPC) using the Eq. (1) proposed by Shaner and Finney (1977):

$$\mathrm{AUDPC} = \sum_{i=1}^{n} \left[\frac{(Y_{i+1} + Y_i)}{2}\right](t_{i+1} - t_i) \tag{1}$$

Table 1
Scale in percentage for evaluation the damage produced by early blight on potato plants. Adapted from Rahmatzai et al. (2017).

Rating of affectation (%)	Description of symptoms
0	No lesion development
1	First visible lesions
10	Lesions between 1-2 mm diameter like small dots on a few leaves mainly old and lower leaves, about 10% of infected leaves per plant.
25	Lesions like frequent spots of < 5 mm diameter on 25% of leaves per plant
50	Lesions like frequent spots of > 5mm diameter in 50% of plant leaves
75	Almost all the leaves have symptoms. Very weakened plant. Large spots in 75% of the leaf area.
100	All leaves are infected and plant is died

Table 2
Active ingredients, effect, dose and date of application during potato crop season.

Active ingredients	Product name	Effect	Rate/ha	Date of application
Metribuzine 70% (wg) p/p	Citation	Weed control	0.5 kg	4-25
Mancozeb 15% + Copper Oxychloride 10% + Cuprocalcium Sulfate 10% (wg)	Covinex Forte mz	Fungi control	1.5 kg	5-15
Chlorantraniliprole 10% + Lambda-Cyhalothrin 5% (zc) p/v	Ampligo	Insect control	0.4 l	5-30
Dimethomorf 7.5% + Mancozeb 66.7%	Spyrit M wg	Fungi control	2.5 kg	6-4
Mancozeb 15% + Copper Oxychloride 10% + Cuprocalcium Sulfate 10% (wg)	Covinex Forte mz	Fungi control	1.5 kg	6-15
Dimethomorph 9% + Propamocarb 50%	Spyrit Pro	Fungi control	2 l	6-28
Dimethomorf 7.5% + Mancozeb 66.7%	Spyrit M wg	Fungi control	2.5 kg	7-11

Where Y_i is the percentage of affected tissue at the i^{th} observation and t is the time (days) at the i^{th} observation, and n is the total number of observations. To estimate the infection speed and the intensity of the damage caused by *Alternaria* in potato cultivars, AUDPC were converted considering duration expressed as number of days (duration) from the first symptoms (1% severity) to the end of the symptoms. The values were expressed following the formula (2) proposed by Fry (1978):

$$\mathrm{r}-\mathrm{AUDPC}=\frac{AUDPC}{duration\ X\ 100} \tag{2}$$

2.5. Aerobiological sampling

An aerobiological sampler Burkard (Manufacturing Co. Ltd., UK) with 7-day recorder spore-trap was placed 1.5 m above ground inside study potato field. The aerobiological sampling was from 19th of April to 31st of July. This sampler is a unit with built-in vacuum pump, designed to sample airborne particles such as fungus spores and pollens. The sampler contains a clockwork-driven drum with a Melinex tape covered by an adhesive substance where particles impact. This device records hourly data. Following the counting method proposed by Galán et al. (2007), the concentration of *Alternaria* was expressed in spores/m^3. The species identified were *A. solani* and *A. alternata* based on their conidial morphology by optical microscopy (Smith, 1990).

2.6. DSS and fungicide schedule

The model selected for the application of fungicides was an adaptation of TOMCAST (Meno et al., 2020) basing on previous proposal of the model (Madden, 1978; Pitblado, 1992; Abuley and Nielsen, 2017; 2019). Leaf wetness and air temperature during this wet period are used to calculate daily disease severity values (DSV) that quantitatively represents favorable days. The threshold considered for these favorable days was 10 DSV, and the fungicide was sprayed when this value was reached. The used active ingredients were selected considering farmer's preferences and the available products in local farm shops. Weeds and pest were controlled as shown in Table 2.

2.7. Yield estimation

The estimation of the tuber yield per hectare was performed considering the planting plot area and tuber yield of two random potato plant per cultivar and plot (control and DSS). Both total and marketable tuber yield (>40 mm) were evaluated. Damaged or rotten potatoes were not accounted for. The results were expressed in t/ha.

2.8. Statistical analyses

AUDPC and r-AUDPC means considering the two data sets (data for control and DSS) were compared by t-test ($P < 0.05$). The differences attributed to the potato cultivar in each plot were analyzed with analysis of variance using the Bonferroni test ($P < 0.05$). These relationships provide information about the mean difference and its variability. Spearman linear correlation analysis was applied to determine the relationships among the meteorological variables and *Alternaria* levels in air, and relationships between AUDPC and *Alternaria* levels. Spearman correlation coefficients were calculated using the weather variables and conidia concentration for the same day and the seven previous days with a significance level of $P < 0.05$. Spearman correlation coefficients between the conidia concentration and AUDPC for the same week and the previous week were also considered. For statistical treatment, the SPSS 21.0 software package for Windows (IBM, Somers, NY, USA) was used.

3. Results

3.1. Phenology stages of potato crop and disease progress: severity, days of infection, AUDPC and r-AUDPC

The crop cycle from sowing day to full senescence had a maximum of 112 days. The potatoes were sown on April 11th, the full senescence of late cultivars was reached on 31st July and the tubers were harvested on September, 6th. The main growth stages and the number of days to the onset of the next phenological stages for each cultivar in field (control plot and DSS plot) were computed (Table 3). The emergence period finished in 28 days after sowing, except for Fleur Bleue and Frisia that took a few more days (35 days). When comparing emergence stage between the DSS plot and the control plot no differences were found.

The leaf development period of cultivars (Fontane, Agria and Red Pontiac) showed some differences according to the plot. The first cultivar to reach full fur coverage was Red Pontiac, with 28 and 35 days for control and DSS plots, respectively. However, this cultivar and Agria were the longest period of maturity. The rest of the cultivars needed one week more. The longest foliar development stage was for Louisa, with 48 days in both plots. Six cultivars had same duration when comparing both plots, stood out Agria and Red Pontiac plants with shorter development in control plot than plants in DSS plot. While, the foliar development for Fontane in control plot lasted a week more. The cultivars reached foliar coverage between rows at the end of June, except Fleur Bleue and Kennebec that did not reach 100% of foliar coverage (Fig. 1).

The maturation phase (M) was measured due to its importance in tuber period, tuber setting and yield. There were important differences among cultivars and plots. The plants growing in the control plot had the

Table 3
Days of the main phenological stage in both plots (DSS and control) counted from sowing. Cultivar code: FB, Fleur Bleue; FR, Frisia; FO, Fontane; LO, Louisa; AG, Agria; DA, Daifla; RP, Red Pontiac; KE, Kennebec; DE, Desiree.

Cultivar	Plot	Emergence	Foliar development	Maturity	Senescence
FB	DSS	35	41	21	13
	Control	35	41	14	20
FR	DSS	35	41	14	14
	Control	35	41	13	15
FO	DSS	28	42	20	20
	Control	28	48	6	15
LO	DSS	28	48	21	13
	Control	28	48	21	7
AG	DSS	28	42	27	13
	Control	28	28	34	14
DA	DSS	28	42	20	20
	Control	28	42	12	15
RP	DSS	28	35	27	20
	Control	28	28	26	8
KE	DSS	28	42	20	14
	Control	28	42	12	8
DE	DSS	28	42	20	20
	Control	28	42	12	15

shortest maturation phase, except Agria, which had the longest one (34 opposite to 27 days) (Table 3). The difference between the control plot and the DSS was 1 week more in Fleur Bleue, Daifla, Kennebec and Desiree.

The senescence for all cultivars was completed between 7 and 20 days. Again, the plants of the control plot reached senescence earlier (Fig. 1). Variations between 1 and 12 days were found when comparing the control and DSS plots. Louisa, Red Pontiac and Kennebec cultivars of control plot had the shortest periods with 7 and 8 days. Whereas, Fleur Bleue reached full senescence in 20 days, 7 days more than Fleur Bleue plants in DSS plot. Considering DSS plot, Fleur Bleue, Louisa, Agria, Kennebec and Frisia completed the senescence in two weeks, and Fontane, Daifla, Red Pontiac and Desiree need one more week.

The severity of early blight in the experimental field by potato cultivar was quantified (Fig. 1). The most of the cultivars in both plots showed the first symptoms (1%) on June 7th (58 days after sowing), during the phase of foliar development or starting maturity. The average severity counted from emergence to senescence was 16% in control plot, and 9% in DSS plot. Although the symptoms started in both plots at same time, there were differences in the progression of the disease achieving all varieties the highest percentage of severity during the senescence stage.

From the onset of symptoms, all varieties showed an upward trend in terms of severity (Fig. 1). First symptoms appeared at same time in all cultivars, excepting Louisa and Red Pontiac, in which started a week later. In the control plot, Frisia and Daifla presented the highest severity (much weakened plants to early blight), with near to 75% of rate of affectation (Table 1). Agria, Red Pontiac, Kennebec, Desiree, Fontane had a severity of 50% and the lowest damages found in Fleur Bleue and Louisa.

However, plants growing in DSS plot showed fewer symptoms. Agria and Kennebec were the most affected cultivar with a value of severity of 33% but it was a low value compared to the control plot. Fontane, Daifla, Red Pontiac and Desiree had a value of 25%, and in the rest of cultivars, few symptoms were observed. Consequently, cultivars in DSS plot lengthened their crop season until the last week of July.

AUDPC and r-AUDPC were calculated for each cultivar and plot. Statistical differences in the mean AUDPC and r-AUDPC values between plots (DSS and control) are shown by asterisk, and differences between cultivars are shown by letters in Fig. 2. AUDPC of control cultivars were higher than the cultivars from the plots treated according to DSS, with an average value of 776.3 and 446.6, respectively. Analyzing the mean AUDPC values of each cultivar by plot (DSS and control), Fleur Bleue, Frisia, Agria and Daifla showed significant differences between plots according the t-test ($P < 0.05$). Although, Red Pontiac, Agria, Fontane and Kennebec had mean AUDPC values higher than 500 units in DSS plots, did not show significant differences respect to the other cultivars. In control plots, the mean AUDPC values of Frisia and Agria were

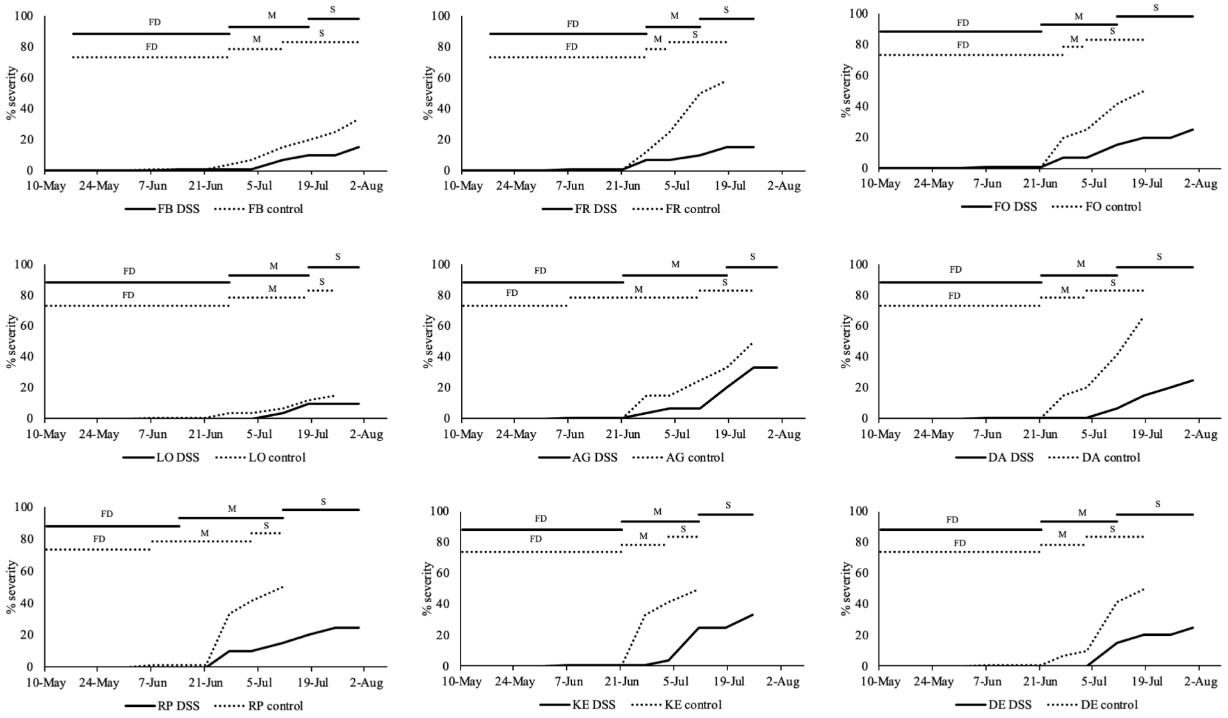

Fig. 1. Disease severity curves for 9 potato cultivars since emergence of plants. Responses to both strategies (DSS and control) and phenological stages affected: foliar development (FD), maturity (M) and senescence (S). Cultivar code: FB, Fleur Bleue; FR, Frisia; FO, Fontane; LO, Louisa; AG, Agria; DA, Daifla; RP, Red Pontiac; KE, Kennebec; DE, Desiree.

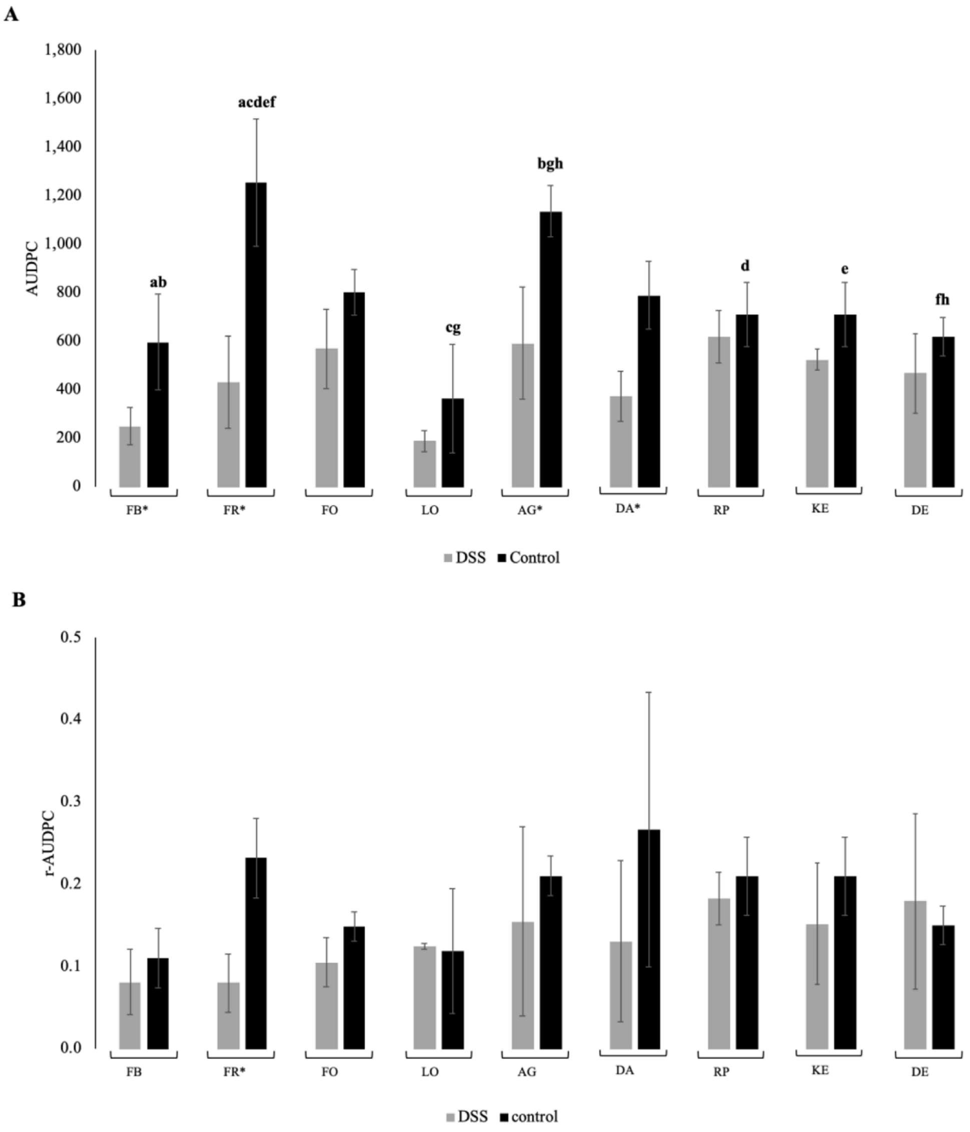

Fig. 2. Accumulated AUDPC (A) and r-AUDPC (B) by cultivar and plot (DSS and control) during growing season. Bars represent the standard error. * Significant differences by plot (DSS and control) according to the t-test ($P < 0.05$). Same letter indicates significant differences between potato cultivars by Bonferroni test ($P < 0.05$).

significantly higher than Louisa, Fleur Bleue and Desiree ($P < 0.05$), which exceeded 1000 units. Red Pontiac and Kennebec also showed a significantly lower mean value with Frisia ($P < 0.05$) (Fig. 2). This fact emphasizes the importance of adjusting the treatments, especially in some cultivars that showed a higher AUDPC curve without treatment.

To estimate the infection speed and the intensity of the damage caused by early blight in the different potato cultivars was calculated using r-AUDPC (Fig. 2). The mean r-AUDPC counted in the cultivars of DSS plots was 0.13, while in control plots was 0.18. Daifla and Frisia had the higher infection speed rate per day in control plot, followed by Agria, Red Pontiac and Kennebec (with values higher than 0.20) (Fig. 2). Considering DSS plots, Red Pontiac and Desiree were the most susceptible cultivars (values of 0.18) and r-AUDPC values were lower in Fleur Bleue and Frisia (0.08). However, only Frisia showed statistically significant differences in r-AUDPC between both plots ($P < 0.05$). Although the number of days of infection was similar between both plots for this cultivar, the disease progressed slower in the DSS plots than in the control plot. As mentioned for Louisa in control plot, the severity of disease caused premature senescence in two of the three observed plants, shortening the mean crop cycle and mean infection period to 36 days. This cultivar had lower accumulated AUDPC and number of infection days in DSS and control plots, but r-AUDPC was high (Fig. 2). Similar results found in DSS plots for Desiree. Desiree had similar AUDPC value than other cultivars, but the infection period was also low, causing an increase in the infection progress rate per day.

3.2. *Weather conditions and airborne Alternaria concentration*

The weather conditions during the potato crop cycle can be considered warm in comparison with other years and little rainy (Fig. 3A). The average temperature of the growing cycle was 17.8 °C, with a maximum daily temperature of 35.0 °C registered in last phases of crop (in July 18th), and a minimum daily temperature of 3.7 °C (in June 9th) during the first days of foliar development. It was raining a total of 25 days and the accumulated rain was of 127.0 mm. Most of these rainy days recorded in the emergence phase (during the first month after planting), whereas from day 69 to 112 there were no rainy days. The average relative humidity during the growing cycle was 86.0%. The daily mean relative humidity was over 80% in the most of days on the stages of leaf development, maturity and senescence (66 days). Relative humidity was always up to 80% in foliar development and maturity phases during 14 days. The daily average of leaf wetness was 9.4 h and within this period

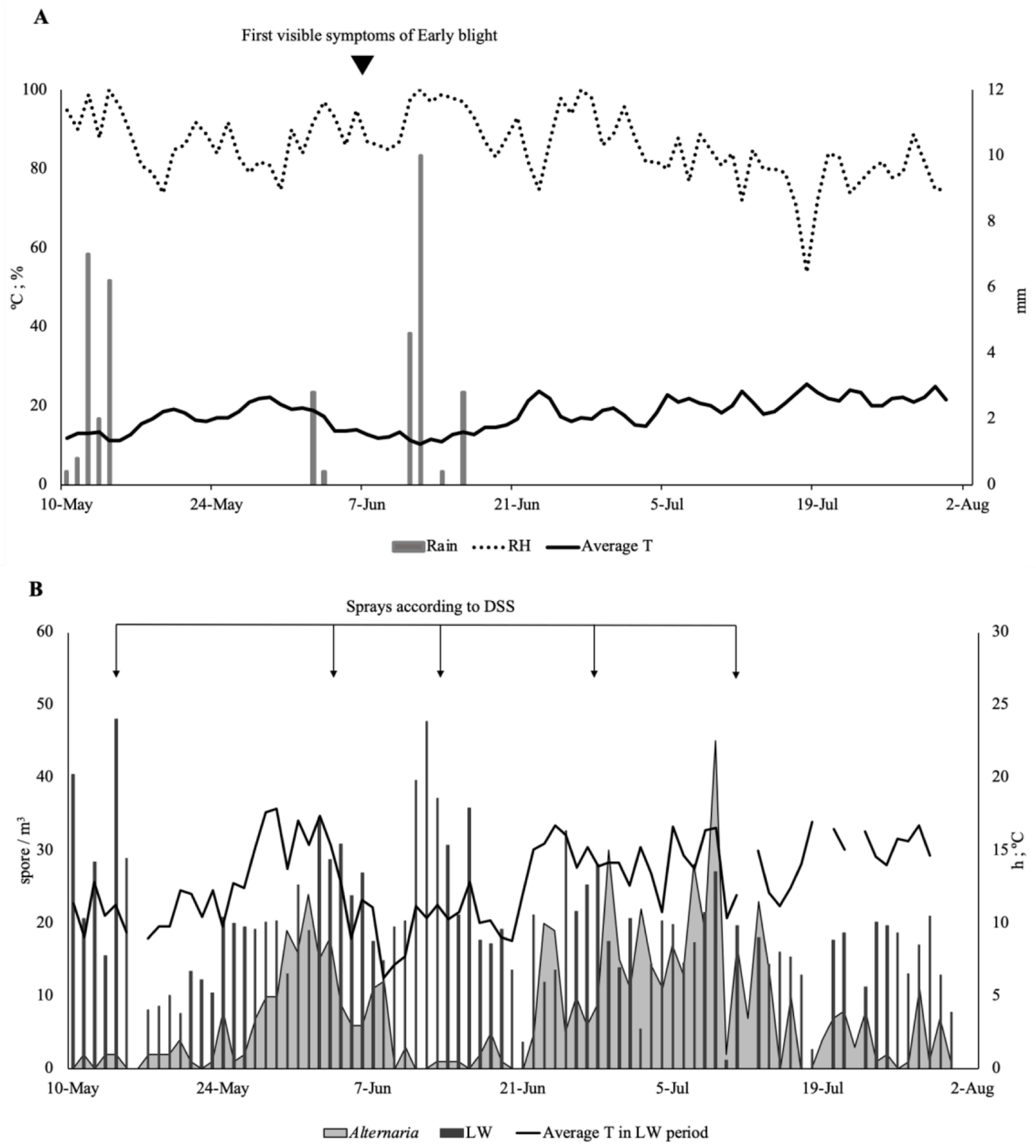

Fig. 3. Weather conditions during potato growing cycle (A) and *Alternaria* concentration in air (B). T: temperature; RH: relative humidity; LW: hours of leaf wetness.

the mean temperature was 13.0 °C, with a maximum temperature of 18.0 °C and a minimum of 6.2 °C.

Aerobiological monitoring was carried out for 104 days, coinciding with the emergence, foliar development of the plants and maturity phase (critical period of early blight infection). *Alternaria* concentrations showed significant daily variations, accounting for a total of 658 conidia during the sampled period. First conidia peaks were observed at the beginning of foliar development (from day 48 to 54), with concentrations above 10 conidia/m^3 (Fig. 3B). From the first days of maturity (day 72) upward trend was noted otherwise, accounting for the maximum concentration of *Alternaria* on day 90 (July 9th) (45 spores/m^3). After July 16th, in the senescence phase, concentrations of pathogen decrease until the last day of sampling (day 112), on July, the 31st. In summary, the first *Alternaria* peaks at the end of May (with concentrations above 15 spores/m^3) caused the first foliar symptoms days later. This fact favored an exponential increase of the infection until the onset of senescence. The first visible symptoms of infection on plants were preceded by daily concentrations of *Alternaria* of 20 spores/m^3 (last days of May) (Fig. 3B). The maximum period of infection (first days of July) was preceded by maximum *Alternaria* peaks and environmental conditions that strongly favored the development of the pathogen. Concretely, more than 6 h of daily wetness leaf and increases in temperature during leaf wetness period (greater than 10 °C) were recorded.

At the same time, disease-forecasting model (DSS) was checked and it alerted of infection risk. In DSS plot, a total of 5 sprays were applied according to accumulated DSV since day 35 (Fig. 3B). These spray-days were 35, 55, 66, 79 and 92 from sowing to begin of senescence.

The relationships between the main meteorological factors (temperature, relative humidity, rain, hours of leaf wetness, temperature during leaf wetness period) and daily *Alternaria* concentration were evaluated using the Spearman correlation analysis (Table 4). High correlation coefficients were found between temperature and *Alternaria* levels of the day, especially when considers temperature up to one and two days before (average, maximum and minimum) ($P < 0.05$). The

Table 4

Spearman correlation coefficients between weather parameters until 7 days before and *Alternaria* airborne concentration.

Previous days	Average T	Maximum T	Minimum T	RH	LW	Average T during LW period	Rain
0	0.259*	0.184	0.326**	-0.025	0.069	0.423**	-0.161
-1	0.316**	0.229*	0.365**	-0.046	0.052	0.459**	-0.119
-2	0.310**	0.252*	0.328**	-0.032	0.042	0.433**	-0.158
-3	0.237*	0.212	0.237*	0.027	0.065	0.373**	-0.192
-4	0.249*	0.18	0.247*	-0.054	0.103	0.391**	-0.205
-5	0.234*	0.193	0.194	0.023	0.046	0.383**	-0.195
-6	0.229*	0.178	0.202	-0.052	-0.091	0.297*	-0.184
-7	0.243*	0.185	0.274*	0.026	-0.078	0.326**	-0.224

T: temperature; RH: relative humidity; LW: leaf wetness period. * ($P < 0.05$); ** ($P < 0.01$).

mean temperature during wet period was the variable with the highest correlation coefficients up to 7 days before ($P < 0.05$) (Table 4). However, no significant correlations between conidia concentration and relative humidity, leaf wetness period and rain were found.

3.3. Relationships between Alternaria concentration and early blight response in the potato cultivars

The relationships between *Alternaria* concentration and disease progression were analyzed by a Spearman correlation analysis (Table 5). The accumulated daily mean *Alternaria* concentration and the mean AUDPC values counted per week were considered. The mean values during the same week and those of the previous week were compared. The correlation coefficients between the mean concentration of conidia of the previous week and AUDPC value for the varieties of the control plot were significant ($P < 0.05$). However, relating conidia and AUDPC of the same week, the correlation coefficients decreased in all varieties. Therefore, the mean *Alternaria* concentration from the previous week influenced the development of disease and this is evident in control plots (Fig. 1 and Fig. 3B). However, in DSS plots, the fungicide application reduced speed disease progression and severity.

3.4. Total and marketable tuber yield of each cultivar at both plots: control and DSS

The disease severity can affect tuber production and its development. Therefore, the total and marketable tuber yield of each variety in both plots (control and DSS) were quantified. The potato cultivars of DSS plots had higher yield than the control plots (both total and marketable tuber yield) (Fig. 4). Fontane, Frisia, Agria and Kennebec were the cultivars with the best total yield, with values between 33.4 and 26.3 t/ha (between 30.2 t/ha and 25.1 t/ha of marketable yield). Following by Desiree, Daifla, Louisa and Fleur Bleue, with productions that ranging between 24 and 22 t (23 to 20 t of marketable production) per planted hectare. Red Pontiac was the least productive cultivar both in total and marketable yield (21.8 and 17.7 t/ha) in the control.

Table 5

Spearman correlation coefficients between *Alternaria* airborne concentrations of same week and a previous week and AUDPC of each plot (DSS and control).

	Control		DSS	
	Same week	Previous week	Same week	Previous week
FB	0.415	0.585*	0.404	0.510
FR	0.480	0.673**	0.412	0.593*
FO	0.562*	0.747**	0.412	0.593*
LO	0.415	0.585*	0.085	0.325
AG	0.415	0.585*	0.415	0.585*
DA	0.562*	0.747**	0.321	0.484
RP	0.625*	0.740**	0.373	0.536*
KE	0.625*	0.740**	0.431	0.632*
DE	0.562*	0.747**	0.318	0.492
Mean	0.442	0.652**	0.424	0.585*

* ($P < 0.05$);
** ($P < 0.01$).

In DSS plot, yields were higher, rising from 40 t/ha in 3 of the 9 varieties. These varieties were Fontane, with 48.0 t/ha (45.8 t/ha of marketable yield), Red Pontiac with 46.3 t/ha (45.1 t/ha of marketable yield) and Daifla with 45.1 t/ha (44.5 t/ha of marketable yield). Next are located Kennebec, Agria, Frisia and Desiree, with total yields between 36.8 and 32.7 t/ha (between 36.1 and 31.0 t/ha of marketable yield) and in the last positions are Louisa and Fleur Bleue with 29.5 and 28.0 t/ha (27.8 and 26.4 t/ha of marketable yield).

Analyzing the control plot and trying to relate the symptoms with the yields, the diversity of the responses of each variety to the disease can be observed. Under natural conditions (control plot), Louisa and Fleur Bleue were cultivars very resistant to the presence of *Alternaria*. Both showed less symptoms reflected in the AUDPC and the r-AUDPC, and lower yield. It is worth mentioned the case of Red Pontiac that under natural conditions is sensitive to the disease and, once infected, quickly reached senescence, as shown by the low value of AUDPC and the high value of r-AUDPC, which indicates that the disease was short and severe in this cultivar. This is reflected in the yield, being the cultivar that obtained the lowest yield in the plot without treatment. The disease in Frisia plants progressed quickly and symptoms were very visible (with the highest accumulated value of AUDPC and r-AUDPC). Fontane is characterized by showing less damage to its aerial parts and a lower growth rate per day (r-AUDPC), letting to obtain the best yields under natural conditions. When fungicides were applied, the marketable tuber yield increased in all cultivars, as was the case of Daifla, Red Pontiac, Kennebec and Fontane, in which yield increases considerably compared to Agria, Frisia and Desiree.

4. Discussion

Agricultural management practices are changing towards strategies to reduce the use of agrochemicals in the control of crop diseases. In most cases, the use of nonselective pesticides, and often without any rules has caused multiples problems, including environmental degradation, resistance to pesticide, negative impacts on natural enemies, and safety for pesticide applicators and the food supply (Damos, 2015). The resistance among potato cultivars to main diseases can be one of the first options to consider reducing damages and ensuring a good production. Good agronomic and horticultural practices, DSS, biological control agents combined with the resistance of cultivars are focusing on seeking safe, eco-friendly and effective alternatives to control potato diseases (Abuley et al., 2018; Jansky and Spooner, 2018; Xue et al., 2019; Meno et al., 2019; 2020).

In recent years, DSS are being adapted for the management of early blight and late blight of potato crops in worldwide agricultural areas (Madden, 1978; Pitblado, 1992; Olanya et al., 2009; Abuley and Nielsen, 2017) and in Northwest of Spain (Escuredo et al., 2019a, b; Meno et al., 2019; 2020). In the case of potato early blight, TOMCAST system was used to successfully forecast first episodes of this disease in the region (Meno et al., 2020). Original TOMCAST model is derived from the FAST model applied for *A. solani* on tomatoes (Madden, 1978) and afterwards was adapted to early blight on potatoes. Different disease

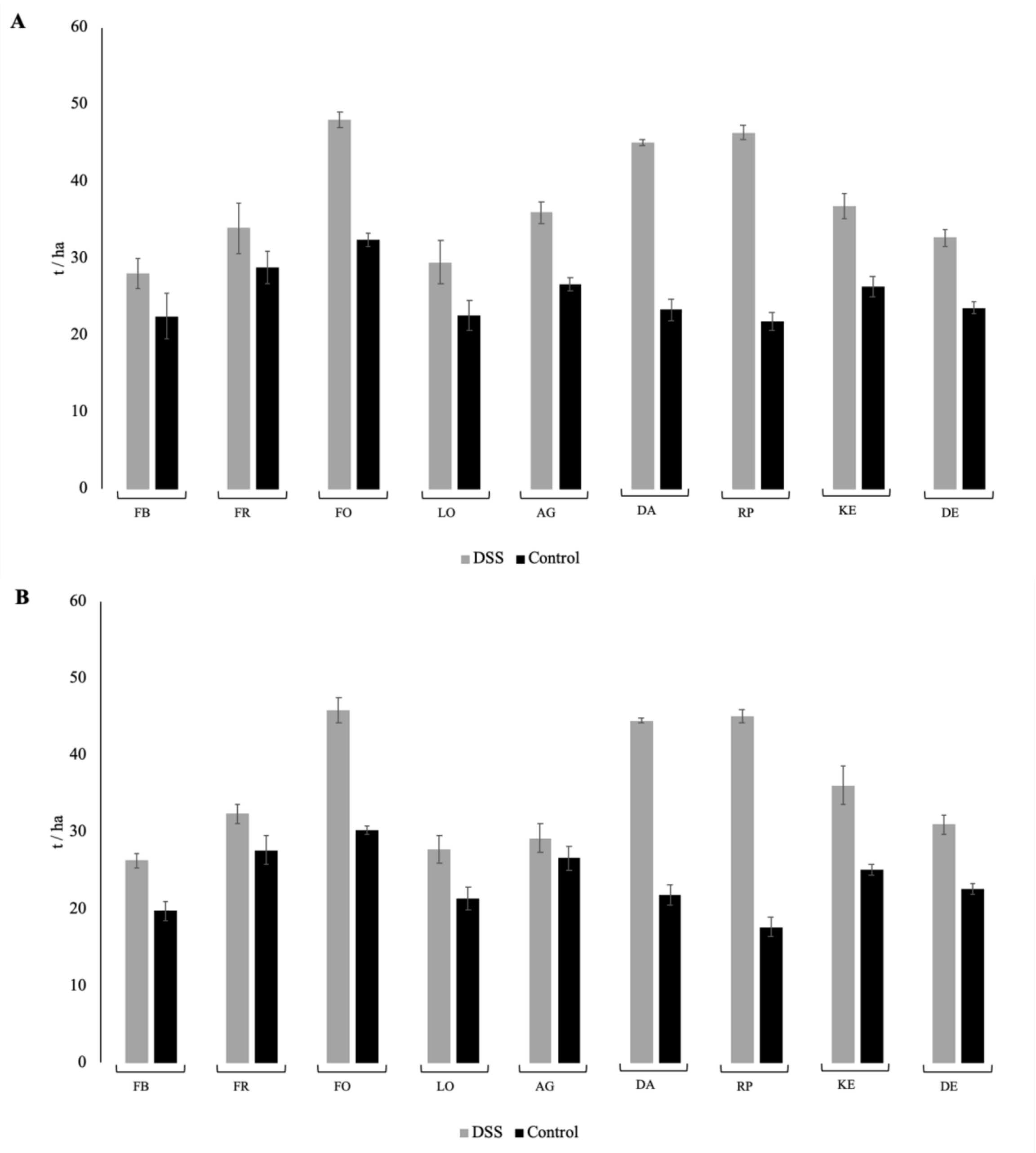

Fig. 4. Bar charts in which tuber yield (A) and marketable tuber yield (>40 mm) (B) were represented (DSS and control). Bars represent the standard error of two sampled-plants yield.

severity values depending on the particularities of the geographical area were validated (Pitblado, 1992; Olanya et al., 2009; Abuley and Nielsen, 2017). For studied region, the more conservative threshold of 10 DSV provided a good prediction of probable outbreaks of early blight (Meno et al., 2020). Common agricultural practices in this geographical area include diseases control measures based on applying different fungicides with an established schedule. Specifically, it is systematic application of a maximum of 15 days, starting when the first symptoms appeared, or when crop reached full coverage stage, without considering risk level of pathogen (Escuredo et al., 2019b). In the region, farmers applies normally an average of over seven fungicide sprays per each crop season basing on these stablished calendars. In this experiment, five applications were enough to reduce early blight pressure in cultivars of DSS plots, even some cultivars showed low infection rate. The results of the application of the DSS allowed a best control of disease, avoiding early senescence in most of cultivars, slowing the progression of disease and ensuring good yields.

Differences in resistance of each cultivar can delay the onset of symptoms of disease and the date of the spray. This resistance can be acquired by effective treatments or owned due to genetic pedigree. The effectiveness of DSS considering cultivars resistance in adjustment should be a part of green management strategies to minimize losses caused by fungal diseases in crops. In the present study, Louisa and Red Pontiac cultivars grown in DSS plot showed symptoms later than other cultivars (5 and 2 weeks later, respectively). Nevertheless, Red Pontiac had an important development of symptoms in control plot when the disease appeared. On the contrary, symptoms for Louisa were slightly higher in the control than in the sprayed plot, being this cultivar together with Fleur Bleue the most resistant cultivars to early blight in this study. These cultivars are recently created and its good response to diseases could be due to recent genetic traits resistant to current strains of diseases and pests and with few previous crosses (Hutten and van

Berloo, 2001). The low yields of Louisa and Fleur Bleue cultivars are related to their high tuberization and small tubers. Although it may also be due to its recent creation and poor adaptation to the climate zone.

Decision-making strategies that combine established models for predict risk of potato early blight outbreaks, such as TOMCAST (Abuley and Nielsen, 2019) and FAST (Shuman and Christ, 2005) with cultivar resistance were successful. Additionally, early plant disease is often characterized by the absence of symptoms, which manifest later, in periods where crop damage is irreversible (Damos, 2015). As a result, the development of DSS for pest management in potato crops is an absolute necessity, which will allow farmers spend less money in chemicals and less time in crop management avoiding crop losses and preserving the environment of rural areas.

Based on the disease severity progress curves and the two epidemiological parameters (AUDPC and r-AUDPC), various studied had found that both cultivar resistance and justified fungicide sprays were important in reducing the development of early blight (Shuman and Christ 2005; Abuley and Nielsen, 2017; Abuley et al., 2018; Abuley and Nielsen, 2019). Untreated plot (control plot) represented the natural development of early blight in field and the response of nine cultivars without inoculation. This natural behaviour in experimental crop fields was verified by other authors in some potato cultivars with differences in susceptibility to early blight (Abuley and Nielsen, 2019; Xue et al., 2019). As expected, the average infection rates calculated by AUDPC and r-AUDPC were significantly higher for untreated cultivars having a faster disease development compared to the cultivars that were treated with fungicide.

There are no levels of adequate resistance to early blight infection depending on the marketable potato species. Some studies focused on the role of *A. solani* infection based on the reduced lesion area of leaf, manifesting the dependence of resistance factor with cultivar of *Solanum* species (Cassells and Kowalski, 1998; Veitía et al., 2014), but without a specific interval. Therefore, the selection of early blight resistant cultivars with attractive marketable tuber characteristics is not easily achieved. Diseases forecasting models do not consider cultivar resistance, possibly motivated by this difficulty. These models only use weather variables and plant phenology. An implicit assumption in most of the models is that all cultivars are equally susceptible to early blight. However, it could be interesting to include in the disease prediction models the type of cultivar considering resistance to early blight (Abuley et al., 2018). For this reason, the development of statistical models that also include epidemiological and aerobiological information has increased to predict the damage by diseases considering the presence of pathogens in growing environment (Pan et al., 2010; Seijo-Rodríguez et al., 2018; Fernández-González et al., 2019; Vélez-Pereira et al., 2019).

Germination and infection of *Alternaria* conidia can be favored by high temperatures and wet periods. Concretely, temperatures between 16 °C and 24 °C, and the presence of moisture in the form of rain, dew or high humidity (> 90%) are favourable conditions for infection of early blight on plants (Van der Waals et al., 2003; Singh et al., 2015; Meno et al., 2019). Xue et al. (2019) denoted that changes in the moisture levels caused higher influence in the prevalence of *Alternaria* than differences in the temperature. From the comparative analysis carried out between the daily meteorological variables, the *Alternaria* levels in the crop environment and the infection rate on the plants, it can be deduced that long periods of leaf wetness and high relative humidity combined with high temperatures during the growing season played an important role in infection. Recently, Campos and Ortiz (2020) denoted as favorable weather conditions for *A. solani* infections temperatures above 22 °C with more than 8 h of leaf wetness. In the present study, a high number of hours of relative humidity (values higher than 80%) during growing season coincided with high *Alternaria* levels. Although, the highest correlation coefficients resulted between the mean daily temperature during the leaf wetness and the daily concentration of *Alternaria*, confirming the strong dependence of the leaf wetness with the spores of the pathogen. Therefore, the leaf wetness duration combined with potato variety are also critical factors to forecast the risk of infection of early blight, as concluded other researchers in Solanaceae (Vloutoglou and Kalogerakis, 2000; Abuley and Nielsen, 2019).

Furthermore, senescing leaves are more susceptible to infection compared to young leaves (Van der Waals et al., 2001; Dita et al., 2006; Abuley et al., 2018; Xue et al., 2019). Some researchers related the response of potato cultivar to early blight with the maturity of plant, being the early-maturing varieties more susceptible (Xue et al., 2019). High severity and AUDPC values were reached by Frisia and Daifla, characterized such as early-medium maturity cultivars. Agria, also accumulated high AUDPC values, it is a late-maturing cultivar, and consequently, accumulated more AUDPC. However, if AUDPC is divided by the infection period (r-AUDPC), it is less than those of early maturation, such as Frisia and Daifla, and similar to other medium and late maturity cultivars (Red Pontiac, Kennebec and Desiree). These results are in agreement with Xue et al. (2019), who also denoted some exceptions of cultivars of medium late maturing with highly susceptibility. Other medium-late cultivars like Fontane, Daifla, Red Pontiac and Desiree showed lower AUDPC values. However, Fleur Bleue and Louisa reached maturity later, and had the lowest disease values. Similar results were found in tomato crop, in which no early maturing had adequate early blight resistance under field epidemics (Gardner and Panthee, 2010). Therefore, the plants more susceptible to early blight are associated with early maturing, older senescing leaves and plants. Due to importance of this phenological stage, maturity was considered in DSS models (Abuley and Nielsen, 2017).

Various research related significant yield losses with potato early blight (Shtienberg et al., 1990; Horsfield et al., 2010; Leiminger and Hausladen, 2012), reaching decreases of 50% if the disease in field progresses uncontrollably (Leiminger and Hausladen, 2012). Shtienberg et al. (1990) reported that tuber bulking stopped when the defoliation by early blight reached 75%. The results of our study showed decreases in yields with severity values of 40-60% in control plots. On the contrary, the cultivars of DSS plots had lower disease development, and consequently lower defoliation and lower losses in yields; corroborating that the longer maintenance of the green leaf area increases the growth of tubers and therefore its yield (Horsfiel et al., 2010). Furthermore, the average yields obtained in this study carried out under the non-irrigated technique coincided with a study carried out in other potato growing area located in Serbia for 10 potato cultivars (Broćić et al., 2016).

Undoubtedly, DSS systems are an essential component of sustainable agriculture. Adjustment to local weather conditions combined with information on disease epidemiology, aerobiological data and genetic resistance of potato cultivars offers an attractive alternative to chemical control because it reduces production costs, ensure yield and quality of tubers and improve environment health.

5. Conclusions

The strong dependence of weather variables with the air *Alternaria* concentration and the early blight symptoms on potato plants, demonstrated the usefulness of incorporating this type of information in the adaptation of DSS in this potato-producing area. At the same time, the response of the cultivar type to disease resistance is crucial information. This is the first study that considers the potato cultivar to measure the risk of the early blight in potato fields of Northwest Spain. With a reduced number of sprays per growing season, it is verified that it is possible to reduce the incidence of the disease and increase yields. It should be noted that monitoring of more growing seasons of the crop is required to compare the results, even to different geographical areas, more cultivars and environmental conditions.

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CRediT authorship contribution statement

Laura Meno: Conceptualization, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Olga Escuredo:** Conceptualization, Formal analysis, Writing – review & editing, Supervision. **M. Shantal Rodríguez-Flores:** Data curation, Writing – review & editing. **M. Carmen Seijo:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no conflicts of interest.

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