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Prediction of Grapevine Yield Based on Reproductive Variables and the Influence of Meteorological Conditions

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Abstract: Climate has a direct influence on crop development and final yield. The consequences of global climate change have appeared during the last decades, with increasing weather variability in many world regions. One of the derived problems is the maintenance of food supply in this unstable context and the needed changes in agricultural systems, looking for sustainable and adaptation strategies. The study was carried out from 2008 to 2017. Aerobiological data were obtained with a Lanzoni VPPS-2000 volumetric sampler, following the Spanish Aerobiological Network protocol. The pollen and flower production was studied on ten vines of the Godello grapevine cultivar. A HOBO Micro Station and a MeteoGalicia station were used to obtain meteorological information. We observed the detrimental effect of rain on airborne pollen presence, and we statistically corroborated the negative effect of high temperatures on fruit set and ripening. We developed an accurate multiple regression model to forecast the grape yield, applying a Spearman's correlation test to identify the most influential variables. The use of aerobiological and meteorological studies for crop yield prediction has been widely used in different crops that suppose important engines for economy development. This enables growers to adapt their crop management and adjust the spent resources.

Keywords: pollination dynamics; reproductive biology; grapevine; yield forecast; Godello

1. Introduction

Aerobiological studies applied on crop yield prediction are becoming a valuable tool for agricultural practices in many crops. The use of pollen information with a forecast purpose has been widely explored for olive crops in the Mediterranean region [1–3], as well as for other important crops in this bioclimatic region, such as almond and grapevine [4,5]. Usually, climatological information is considered for aerobiological analyses because of their influence on aerobiological processes, such as pollen release or dispersion, and crop development. Meteorological factors exert a direct effect on the onset and duration of the phenological stages, acting as one of the main inputs that plants need to complete their vegetative-productive cycle [6].

Climatic conditions have a marked influence on grape and wine production, as factors such as temperature, light and humidity affect vegetal growth and development [7,8]. Combined with the edaphic elements (as soil water reserve or effective soil depth), these environmental components are considered the most important factors to define the winegrowing and production suitability of a region [9]. Furthermore, adverse weather conditions such as hailstorms may reduce grape yield by damaging flowers and fruits, affecting the total leaf area and the phenolic profile of berries at harvest [10]. Hail damage on grapevine yield increased across the European winegrowing regions due to climate change impacts [11]. Rainfalls wash pollen grains from the atmosphere or the stigma surface, which leads to a loss of fertilisation efficiency and a decrease in fecundated flowers [12].

Climate change has important consequences on biodiversity and ecosystem functioning. There are being registered many climate shifts in different world regions, such as the contraction of polar climate zones and the expansion of arid ones. This is the result of changes in intensity and frequency of extreme weather phenomena, such as extreme temperature events [13]. The intensity, frequency and duration of heat waves are projected to increase during the 21st century, as well as the frequency and intensity of droughts, which are projected to increase, particularly in the Mediterranean region and Southern Africa [14]. Studies conducted by [15] had confirmed that recent observed changes along European viticultural regions followed the climate change predictions, especially for the Iberian Peninsula, where a high increase of drought risk was detected. At a long-term scale, weather factors such as late spring frost in a warmer climate are expected to reshape the grapevine cultivars distribution in Europe [16]. Nevertheless, other studies suggested the increase of agrobiodiversity as an effective buffer of climate change effects on winegrape crop, using more climatically suitable cultivars for the climate warming. The authors of [17] found drastic reductions in winegrowing losses under warming scenarios with cultivar diversity.

Another important point to consider for a crop production study are the physiological and morphological characteristics influenced by environmental conditions but deeply related to genetic load and expression. Flower formation and development in grapevines are highly influenced by environmental, genetic and cultural factors, which contribute to its variability [18].

The aim of the present study was to develop a prediction model to forecast the grape production for the Godello cultivar, one of the four autochthonous dominant white varieties in the Ribeiro Designation Origin area, which represent an important percentage of the Northwest Spain total production [19]. Aerobiological and meteorological variables, combined with pollen, flowers and grape production data, were considered to achieve an accurate prediction model for the final grape production as well as to assess the climatic influence on vegetal growth and the main detrimental factors affecting the considered cultivar. The development of this kind of model makes possible an adjusted crop yield prediction some months in advance, enhancing possible fraud detection due to the introduction of foreign grape by the establishment of a preliminary grape weight value prior to the official measure of the allowed grape varieties produced by the wineries covered by a Designation of Origin, the optimisation of the cultural and post-harvest tasks or the crop insurance hiring. Additionally, this information could be used to know the adaptation of the cultivars to the changing environmental conditions.

2. Material and Methods

2.1. Temporal and Geographic Delimitation

The study was conducted from 2008 to 2017 in a vineyard located in Cenlle (Ourense) in Northwest Spain, which belongs to the Ribeiro Designation of Origin that actually covers a total area of 2250 ha (Figure 1). This winemaking region, watered by the Minho river, is defined as temperate and warm, sub-humid and with very cold nights according to the Multicriteria Climatic Classification System (MCC) [19]. Natural barriers that protect this territory from sub-Atlantic storms and its southern situation in Galicia favour the Oceanic-Mediterranean transitional climate of this region, with warm temperatures and considerable precipitation. Steep valleys and hillsides characterise the geomorphological structure of this area, with soils that have a granitic origin with a significant content of stones and gravel [20].

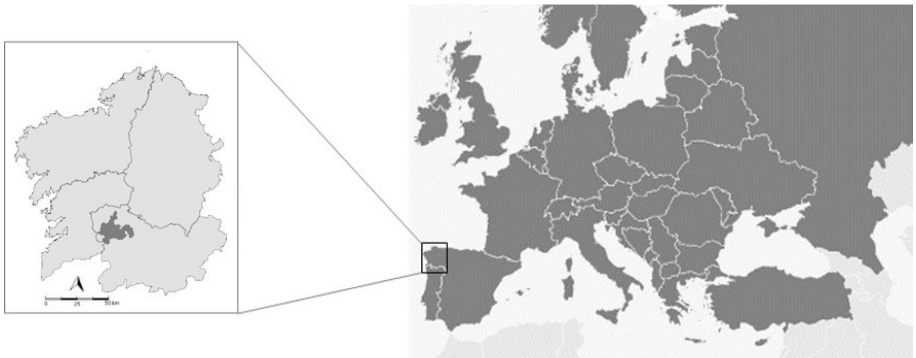

Figure 1. Location of the Ribeiro Designation of Origin area in South Galicia, one of the main five Galician wine Designations of Origin, and its situation in Europe.

2.2. Plant Material and Grape Production Data

Ten vines of the Godello grapevine cultivar were considered for pollen and flower production studies. The same ten plants were analysed over the study years, from 2008 to 2017, which were initially randomly selected among the Godello plot. The studied vineyard is enclosed in a multi-varietal plot comprising four autochthonous Galician white cultivars, Treixadura, Godello, Loureira and Albariño, with a distance of 10 m between plots. The Godello plot considered in the present study covers an area of 2641.71 m^2, composed by 20 rows of vines each one with 50 vines at 1-m spacing trained on a vertical shoot trellis system and row spacing of 2 m.

The grape production data of the entire Ribeiro D.O. are annually provided by the Ribeiro Regulatory Council and published on its official website www.ribeiro.wine/es. The company "Viña Costeira S.R.L.", registered as part of this Designation of Origin and owner of the studied vineyard in the present study, records the grape production of each plot in kilograms per hectare, providing us these yield data after harvest.

2.3. Aerobiological Study

A Lanzoni VPPS-2000 volumetric pollen trap [21] was used for the detection and identification of airborne pollen and the spores of the main phytopathogenic fungi (*Botrytis cinerea*, *Plasmopara viticola* and *Erysiphe necator*) in the atmosphere of the vineyard. It was located in the central part of the plot, at 2 m above ground to minimise difficulties in pollen trapping by plant growth. The sampling period took place during the active cycle of *Vitis vinifera*, from 1 April to 30 September. A continuous flow of 10 L of air/minute was maintained in the sampler and a Melinex tape coated with a 20 g/L silicone solution was used as trapping surface. The tape support spins at 2 mm/h, giving an autonomy of seven days. After this period, the Melinex tape was changed and the exposed tape was cut into seven pieces that were mounted on separate glass slides. *Vitis vinifera* pollen grains were identified and counted using an optical microscope and following the proposed model by the Spanish Aerobiological Network (REA) [22]. The *V. vinifera* pollen grains were identified as sub-spherical to triangular, tricolporated with three furrows and three pores, and 17-28 µm in diameter [23,24]. The Main Pollen Season (MPS) was assessed by means of the method proposed in [25], following the [26] protocol. The MPS accounted for the 95% of the total annual pollen recorded, starting when the accumulated sum of pollen reached the 2.5% of the total annual pollen, and ending when 97.5% of the total pollen was reached. The Seasonal Pollen Integral (SPIn) was calculated by summing the daily pollen grains/m^3 concentrations over the MPS. Results of pollen counts were expressed as pollen when they were referred to total values of the considered period, or pollen grains/m^3 of air when referring to daily mean values [27].

2.4. Pollen and Flower Production Study

Pollen and flower production was studied on 10 selected vines of the Godello cultivar maintained over the studied years. Each annual value corresponded to the average value of the 10 considered plants for the different variables. The number of inflorescences, tertiary branches (third order ramification in the inflorescence) and flowers per plant were estimated in the phenological phase BBCH-57 [28], corresponding to inflorescences fully developed, with flowers separating. To estimate the number of flowers per vine, we observed that 25 flowers composed a tertiary branch as a mean value, obtained from the flower count of one inflorescence on each one of the ten selected vines. To assess the number of anthers per flower, we observed in all collected flower samples that the *Vitis vinifera* androecium of the Godello cultivar is comprised of five stamens, each one with a bilocular anther, which coincided with previous descriptions of the *Vitis vinifera* floral biology and morphology [18].

The number of pollen grains per anther was calculated following the volumetric method described in [29]. Anthers were collected from grapevine flowers near to anthesis, in the BBCH-57 stage. Each anther was placed in 0.5 mL of ethanol 70% (v/v) with two drops of 1% basic fuchsin for pollen grains staining. The sample was crushed in the tube and vortexed to its homogenisation. A volume of 10 μL of this dilution was transferred to a slide for microscope analysis and total pollen grains were counted with an optical microscope NIKON ECLIPSE E100 at 400× magnification. A total of 27 anthers were analysed corresponding to three inflorescences of each vine, selecting three flowers per bunch and three anthers per flower. Three replicates were analysed for each sample. The number of pollen grains per anther was obtained by extrapolation to the total dilution volume.

We calculated the pollen grains per vine considering the number of pollen grains per anther, the constants of 5 anthers per flower and 25 flowers per tertiary branch, the number of tertiary branches per inflorescence and the number of inflorescence. With all this information, it is possible to know the number of pollen grains per flower and flowers per vine, which defines the number of pollen grains per vine.

2.5. Meteorological Data

Meteorological information was obtained from a HOBO Micro Station data logger, located at the central part of the cultivar Godello plot and in the same bracket than the aerobiological trap, at 0.75 m above ground level. The monitored daily parameters with this station were maximum temperature, average temperature and minimum temperature. Information about the precipitation was obtained from the Galician Institute for Meteorology and Oceanography METEOGALICIA station in Leiro (at 5 km from the studied vineyard). Based on these daily data, an average of 10 days, 15 days and one month periods were calculated for each temperature parameters from 1 April to 30 September for each studied year, from 2008 to 2017. The rainfall values were obtained from the sum of rainfall daily values during 10 days, 15 days and one month periods from 1st April to 30th September, from 2008 to 2017. Each one of the considered variables for statistical analysis were formed by the corresponding ten-days, fifteen-days and monthly periods over the studied years.

2.6. Statistical Analysis

A Spearman's correlation test was applied to determine the influence of meteorological conditions, pollen and flowers production parameters on grape production using the 2008–2016 data set. We applied this non-parametric statistical analysis due to the non-normal distribution of data. Significance was calculated for $p \leq 0.01$ and $p \leq 0.05$. In order to detect possible redundant correlation among the variables and prevent its use for model development, we calculated correlation matrix in six blocks for meteorological variables, considering the ten-days, fifteen-days and monthly periods, and a separated block for pollen and flower production variables. We used the R software version 3.5.3 [30] for this purpose, with the 'corrplot' 0.84 package for graphs generation [31].

Based on the correlation results, we developed a multiple regression model to forecast the final grape production considering the 2008–2016 data set. The 2017 data were used for model validation. Pollen and morphological production variables were considered as discrete variables: inflorescences/vine, tertiary branches/vine, flowers/vine, pollen/anther, pollen/vine and the total sum of pollen grains/m^3 of air over the season (SPIn). The accuracy of the obtained model was assessed by means of a lineal regression analysis between the observed grape production and the expected grape production values obtained by the model, and a Leave-One-Out Cross Validation (LOOCV) to determine the forecast reliability by the iterative prediction of each observation by means of all surrounding data as training data set [32]. The 2008–2016 data set was used as a training set in order to calculate the training error rate as the Root Mean Square Error (RMSE) of the LOOCV iterations. The standard deviation was calculated in order to estimate the error magnitude. The 2017 year was used to describe the test error rate since it was not included for model development, with the application of a *t*-test for dependent samples for the evaluation of significant statistical differences between real and forecast grape production in 2017. We used the IBM SPSS Statistics 25 software for these statistical analyses.

3. Results

3.1. Aerobiological Analysis

Vitis vinifera L. Godello main pollen seasons were monitored between 2008 and 2017 from the middle of May to the end of June (Table 1). This period, which identifies the main pollen presence in the atmosphere, varied between the considered seasons, with a mean duration of 19 days and ranging from 15 to 27 days (in 2011 and 2012, respectively). The mean start date for the MPS was on 29 May and the mean end date on 16 June. In both cases, there is a month gap between the earliest and latest dates for starting and ending MPS among the considered years. The latest dates for the start and the end dates were detected in 2013, on 14 June for the start and 30 June for the end. The earliest dates for the MPS start and end also coincided in the same year, in 2011, with the beginning on 14 May and the end on 28 May. The 2011 season was additionally the year with the shortest MPS duration with 15 days (Table 1).

The earliest peak date of airborne pollen concentrations was recorded on 23 May 2011, while the latest was registered on 23 June 2013. This monthly deviation among the studied years for the peak date indicates a marked year-to-year difference on the pollination season. The maximum peak value of daily pollen concentration was registered in 2011 with 64 pollen grains/m^3, which coincided with the earliest peak date among the studied years. On the other hand, the minimum daily pollen concentration was registered in 2008 with 7 pollen grains/m^3 (Table 1).

Table 1. Total pollen (SPIn), Main Pollen Season start, end and duration, and seasonal peak values for each considered year.

Year	SPIn (Total Pollen)	Main Pollen Season (MPS)			Seasonal Peak	
		Start Date	End Date	Duration (Days)	Peak Date	Peak Value (Pollen Grains/m^3)
2008	84	8-June	27-June	20	12,13,14,20-June	7
2009	222	30-May	17-June	19	1-June	34
2010	225	29-May	21-June	24	7-June	34
2011	226	14-May	28-May	15	23-May	64
2012	142	29-May	24-June	27	6-June	17
2013	336	14-June	30-June	17	23-June	48
2014	224	29-May	13-June	16	6-June	56
2015	94	24-May	10-June	18	29-May	28
2016	293	6-June	24-June	19	21-June	42
2017	282	15-May	1-June	18	24-May	49

Temperature variations and precipitation events seem to produce a marked effect on the pollen presence in the atmosphere. By representation of the airborne pollen concentrations evolution with mean and maximum temperature and precipitation (Figure 2), we observed that rain events during the pollination period coincided with marked decreases in the airborne pollen. In 2008, this direct effect was observed on 15 and 16 June, with 2.2 and 6.6 mm of rain, respectively, and a decrease in pollen concentrations that were the highest into the MPS (of 7 pollen grains/m^3) to very low values of 2 pollen grains/m^3.

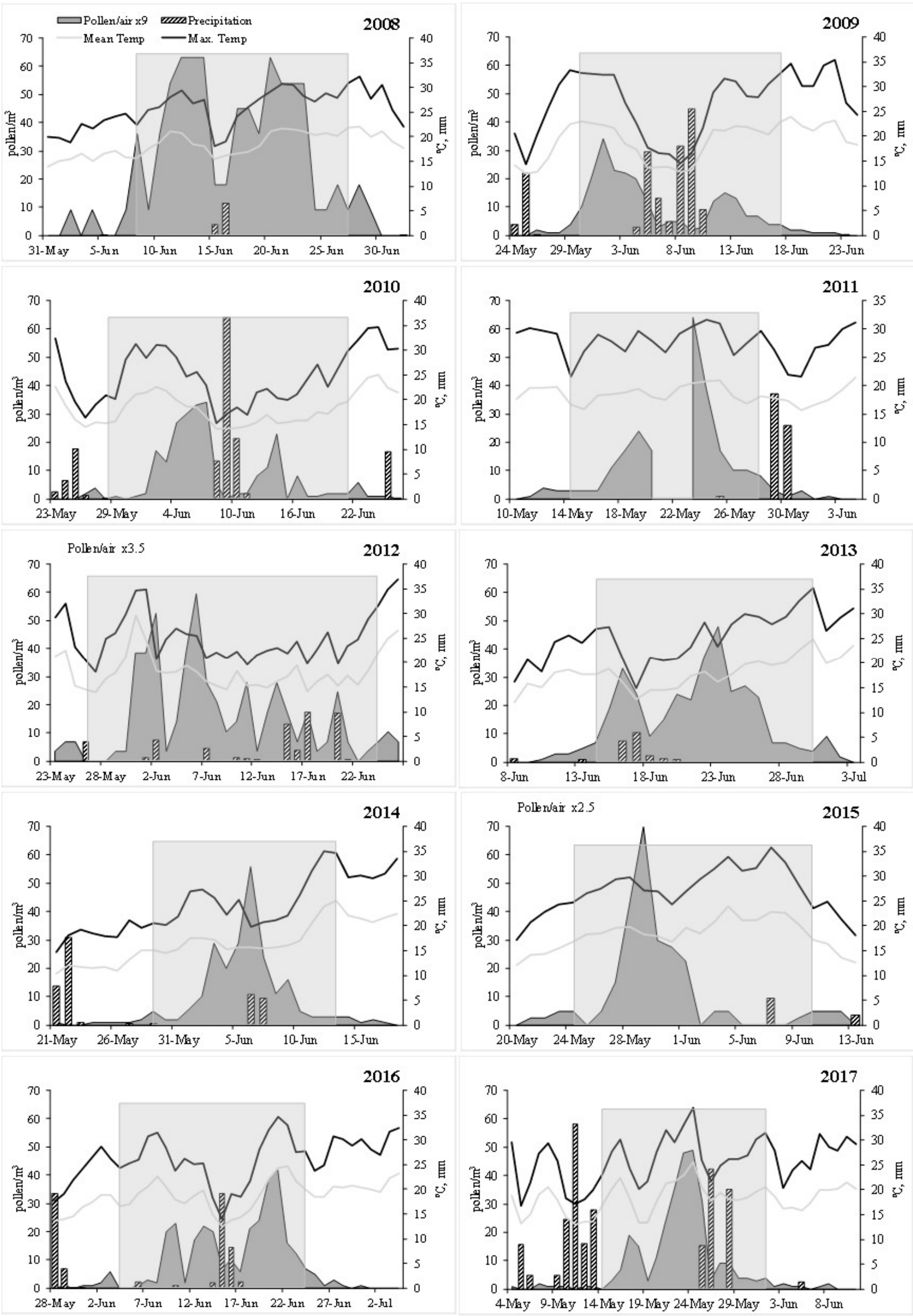

Figure 2. Airborne concentration of *Vitis vinifera* pollen (grey area), mean daily temperature (grey line), maximum daily temperature (black line) and precipitation (bars) during the Main Pollen Season (MPS) (grey squares) for each studied year. Pollen sampling was interrupted in 2011, from 21 to 22 of May, due to power cuts.

In 2009 this detrimental effect was observed in the middle of the MPS, with a period of rain in consecutive days from 4 to 10 June and much rain accumulated on 5 June (16.8 mm), 8 June (18 mm) and 9 June (25.6 mm). The continuous rain period made the airborne pollen concentrations descend, which previously were the maximum MPS values, containing the seasonal peak of 34 pollen grains/m^3 on first June.

During this precipitation period, the pollen concentrations went down to a range of 2–5 pollen grains/m^3 for the 6–10 June period. The same situation was observed in 2010 and 2016, with heavy rain events that promoted a marked decrease in airborne pollen concentrations.

In the 2012 MPS, the airborne pollen records were irregular and oscillating. Pollen concentrations were not very high in this year and rain was widely distributed over the entire MPS, with several events on 1–3 June (0.8, 4.2, 0.2 mm, respectively), 7–8 June (2.6 and 0.2 mm), 10–13 June (0.8, 0.6, 0.4 and 0.2 mm), 15–17 June (7.4, 2.2 and 10 mm) and 20–21 June (9.8 and 0.4 mm). This descend on the pollen concentrations promoted by rain was also observed in 2017, where the occurrence of rain on 25 May, 26 May and 28 May (8.8, 24.2 and 20 mm, respectively), just after the seasonal pollen peak, of 49 pollen grains/m^3 on 24 May, promoted a fast decrease in the airborne pollen concentration. Moreover, temperature dropped during the precipitation events, which has an added adverse effect on the atmospheric pollen presence (Figure 2).

Conversely, temperature rises coincided with high airborne pollen concentrations and in many cases with the highest seasonal pollen peak. The beneficial effect of the mean and maximum temperature rise on the presence of atmospheric pollen was clearly observed in 2008, 2009, 2016 and 2017. In these years, the pollen increases seem to adjust with temperature rises (Figure 2). The average of mean temperatures during the MPS of the considered years 2008–2017 was 18.5 °C, and the average for maximum temperatures was 26.2 °C.

3.2. Pollen and Flower Production

The production of inflorescences, flowers, pollen per vine and pollen per anther showed similar fluctuations among the considered years, from 2008 to 2017 (Figure 3).

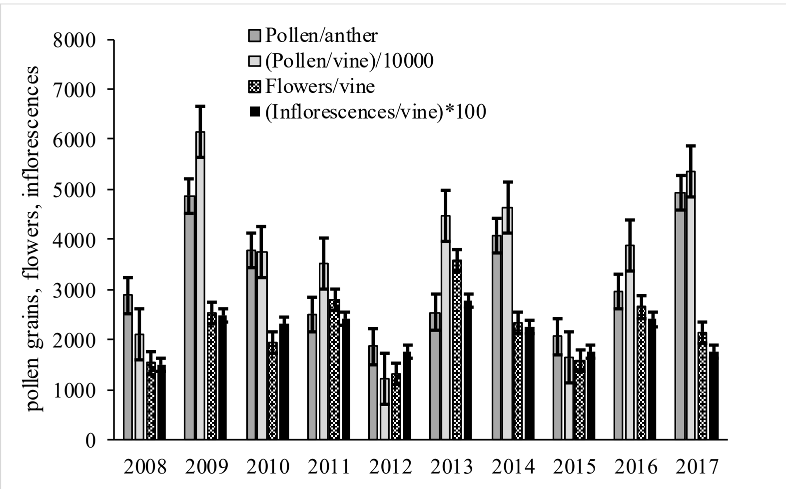

Figure 3. Total annual production of flower, inflorescences, pollen grains per anther and pollen grains per vine for the studied seasons 2008–2017. Standard error of the mean for each variable in bars.

The flowers per vine, which presented an average value of 2238 flowers/vine for the considered plants among the complete studied period, showed the maximum in 2013 with 3581 flowers/vine and a minimum in 2012 with 1308 flowers/vine. The maximum annual record of flowers/vine coincided with the highest inflorescences' number that was also registered in 2013 with 28 inflorescences, while the minimum was registered in 2008 with 15 inflorescences. The minimum records of pollen per anther and the pollen per vine coincided in the same year, in 2012, with 1863 pollen grains/anther and 12,138,912 pollen grains/vine, respectively. The maximum record of pollen per anther was obtained in 2017 with 4937 pollen grains/anther, while the maximum record of pollen per vine was registered in 2009 with 61,631,026 pollen grains/vine (Figure 3).

Nevertheless, important differences were found in 2011, 2014 and 2017, showing a dissimilar behaviour on the different pollen-flowers-inflorescences production variables. In 2011, despite the increase of 855 flowers/vine with respect to the previous year, the pollen/anther markedly decreased (from 3780 in 2010 to 2506 pollen/anther) and the pollen/vine had a slight descend (from 37,377,906 in 2010 to 35,083,187 pollen/vine). In 2014, these variables changed inversely, with a notable increase in pollen/anther (from 2546 to 4084 pollen/anther) and a slight increase in pollen/vine respect to the previous year (from 44,739,674 to 46,331,441 pollen/vine), but the number of flowers/vine descended to 1258 flowers with respect to the previous year. In 2017, the pollen/anther and pollen/vine markedly increased, from 2953 in 2016 to 4937 pollen/anther, and 38,773,450 in 2016 to 53,637,941 pollen/vine. Despite this, the number of flowers slightly descended to 504 flowers (Figure 3).

3.3. Statistical Analysis

A Spearman's correlation test was applied to assess the main weather, pollen and flower production variables that have a significant influence on final grape production.

The statistically significant correlations were mostly related to meteorological variables (Figure 4). Regarding the correlations of meteorological variables with grape production, we found the highest significance level ($p < 0.01$) for the variables of the first ten-days of August maximum Temperature, the second ten-days of July maximum Temperature and the second ten-days of April Rain, and the monthly July maximum Temperature, April Rain and May Rain, all of them with a negative coefficient, which indicated a negative influence on the final grape production (Figure 4). In the case of pollen and flower production variables, we only found one correlation with grape production, the number of inflorescences per vine, but with a low p-value ($0.1 > p > 0.05$) (Figure 5).

Furthermore, we observed in the correlation matrix of the meteorological variables, divided in six blocks, as well as in the matrix for pollen and flower production variables, some strong correlations between variables tightly related, as the positive correlations found for mean and maximum temperatures in the same period, or the negative correlations of these mean and maximum temperatures with rain for the same studied period that could reflect the air temperature decrease the effect of rainfall from a cooler atmosphere layer, as raindrops exchange heat with the warmer air near to the ground due to the evaporation of part of the waterdrops.

Among the considered pollen and flower production variables, we found strong correlations possibly related with some secondary variables derived from primary variables, as the flowers/vine deriving from the number of tertiary branches and inflorescences or the pollen/vine derived from the pollen per anther and the number of flowers. To prevent the effect of these relations in the regression model, we decided not to consider variables where redundant correlations were found, and instead just one of the pollen and flowers production variables, the inflorescences/vine, since it showed statistical influence on grapevine yield.

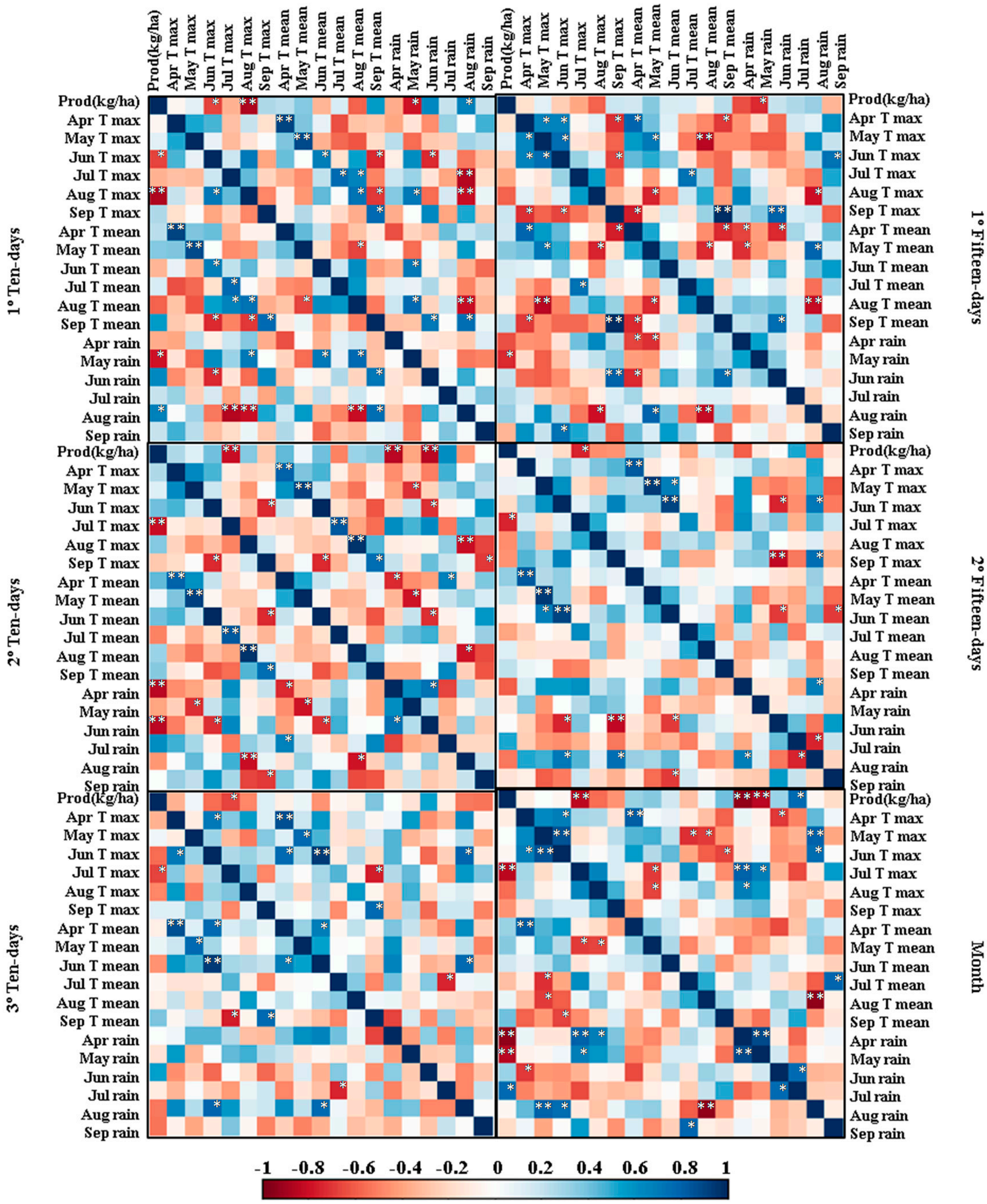

Figure 4. Spearman's rank correlation coefficients between grape production and meteorological variables with the considered period durations of ten-days, fifteen-days and month for the 2008–2016 data set. Coefficient values were expressed in colours (referred to the lower legend) and the significance level was represented as * $p < 0.05$, ** $p < 0.01$.

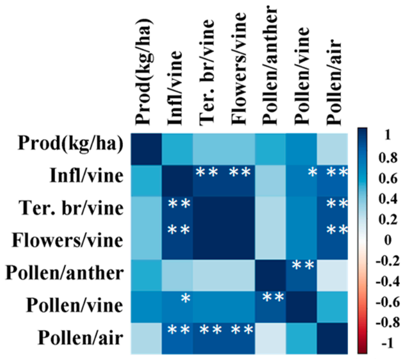

Figure 5. Spearman's rank correlation coefficients between grape production and pollen and flower production variables for the 2008–2016 data set. Coefficient values were expressed in colours (referred to the right legend) and significance level was represented as * $p < 0.05$, ** $p < 0.01$. Infl: inflorescences; Ter. br: tertiary branches.

Based on the Spearman's test results, we developed a multiple regression model to forecast the final grape production of the Godello cultivar (Table 2).

The Adjusted Coefficient of Determination (R^2) was 0.9893, which indicated that the obtained equation explained a large proportion of data variance, higher than 95%.

The accuracy of the obtained model was tested by means of a lineal regression analysis between the observed grape production and the expected values obtained by the model. This regression showed an R^2 of 0.993 ($p < 0.0000$), which revealed the quality of the model to forecast purpose (Figure 6).

Table 2. Regression parameters of the yield prediction model developed for the Godello grapevine variety.

Variable	Coeff (SE) [a]	*p*	$R^2 = 0.993$
Intercept	10,242.150 (1356.392)	0.00065	Adjusted $R^2 = 0.989$
11–20 July max. T [b]	−151.510 (37.282)	0.00969	SE = 260.95
11–20 April Rain [c]	−51.596 (3.409)	0.00002	$F(3,5) = 247.80$
Inflorescences/vine [d]	130.025 (25.490)	0.00377	$p < 0.00001$

[a] Regression coefficient (Standard Error). [b] Average of maximum daily temperatures from 11 to 20 July. [c] Sum of the accumulated daily rain values from 11 to 20 April. [d] Average value of inflorescences per vine for the ten studied plants in the considered year.

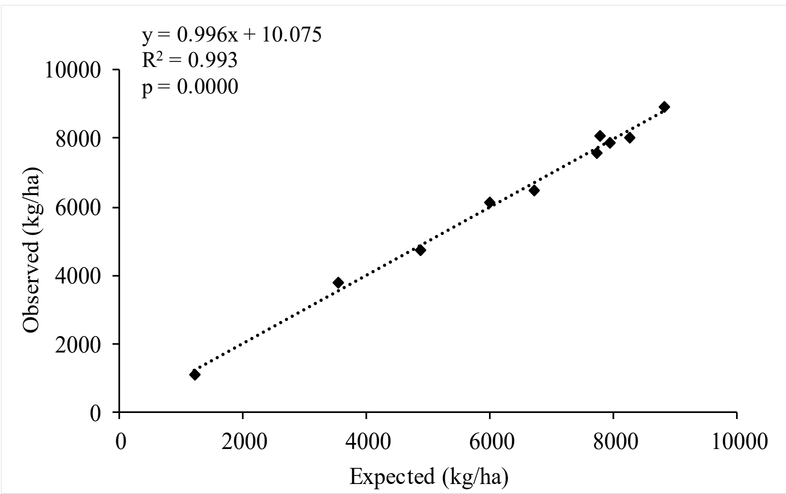

Figure 6. Lineal regression analysis between the observed grape production and the expected production values obtained by the model in kilograms per hectare (kg/ha).

This was reinforced by the LOOCV procedure (Figure 7), since the RMSE value of 440.27 was lower than half of the Standard Deviation of the considered values (RMSE ≤ 0.5*SD), which can be considered as an acceptable error level following the [33] and [34] criterion.

The graphical representation of the observed grape production in kilograms per hectare (kg/ha) with the expected production obtained by means of the proposed model, showed an excellent data fit, with a difference of just 144 kg/ha between real and forecast grape production in 2017, the validation year not included for model development (Figure 8). Additionally, we applied a *t*-test for dependent samples including 2017 data, and no significant differences were found, with a *p*-value of 0.825 (marked differences are significant at $p < 0.05$) (Table 3).

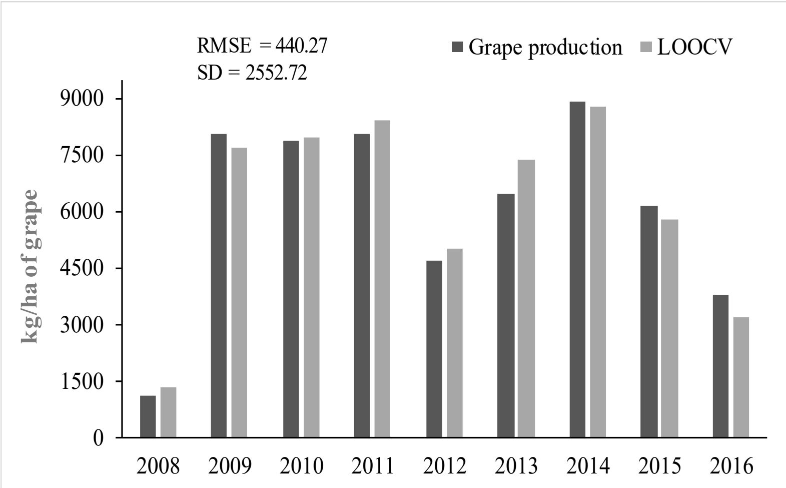

Figure 7. Leave-One-Out cross validation procedure (LOOCV) for grape production along the 2008–2016 data set.

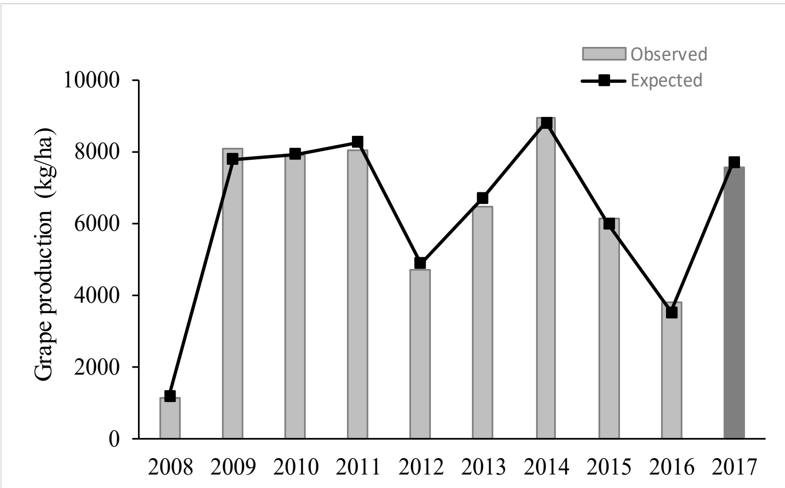

Figure 8. Evaluation of the graphical adjust between real and forecast grape production in kg/ha. The year 2017 was used for model validation, it was not included for model construction.

Table 3. The *t*-test for dependent samples between real Godello grape production in kg/ha and the expected production values obtained by the model.

Variable	*Mean*	*Std.Dv.*	*N*	*Diff.*	*Std.Dv.Diff.*	*t*	*df*	*p*
Prod. Godello	6267.910	2423.226						
Expected	6282.283	2424.433	10	−14.374	199.740	−0.228	9	0.825

4. Discussion

The prediction of crop yield from the Aerobiology point of view is a powerful tool for yield management that has been widely used in the last decades [35–37]. Pollen release and dispersal are key factors acting in the pollination process, which determines the final crop production. As the 2030 AGENDA claims, the variability on climatic conditions is increasing, making comprehensive and more detailed studies on the agro-ecosystems necessary in order to prevent serious consequences on final crop quantity and quality and ensure food availability for humanity [38]. The meteorological variability affects crops in different ways and indirectly alters the pest and disease incidence and severity. Therefore, it is necessary to adapt our agronomic system in the present climate change scenario to provide more flexibility and reaction ability to growers, including the prevision of final crop production, the identification of the most important influential factors and the potential risk moments for phytosanitary treatment applications. All this with the final goal of achieving a more sustainable production and resources consumption that increases the productivity and strengthens the adaption ability to extreme weather, droughts, flooding and other disasters while progressively improving land and soil quality [38].

Pollen release and dispersal are highly influenced by weather conditions, especially temperature and precipitation. The vineyard specific meteorological conditions significantly influence airborne pollen levels detected in the atmosphere. Low temperatures and rainfall events during flowering drastically reduce the airborne pollen concentration, as temperature is considered one of the most influential factors on pollen concentrations present in the atmosphere [39]. Our results from the analysis of the weather conditions during the pollination period corroborated these affirmations. Rainfall events affected pollen dispersal processes, causing a marked decrease on atmospheric pollen concentration due to atmospheric washes [40]. This active deposition can act on the atmospheric pollen content by means of two mechanisms, the *rainout* in the case of submicronic particles transported by little raindrops or ice crystals by molecular diffusion, or the *washout* in the case of particles larger than 1 µm that are retained in raindrops, hail or snowflakes due to collisions [41]. The meteorological conditions considered as ideal for pollination are temperatures around 20 °C with dry weather and a slight wind, while temperatures of 15 °C or lower with rain produce a decrease in the efficacy of the fertilisation [42]. Furthermore, temperatures between 26.7 and 32.3 °C are considered optimal for ovule germination and the growth of the pollen tube [43]. Our results showed that the climatic conditions during the pollination period were very favourable to a correct fertilisation, since the average mean MPS temperature for all the MPS (2008–2017) was 18.5 °C, with the maximum mean MPS temperature in 2015 (19.7 °C) and the minimum in 2014 (17.3 °C). In the case of maximum temperatures, the average of maximum MPS temperatures for the study period was 26.2 °C, with the maximum MPS temperature in 2015 (28.9 °C) and the minimum in 2010 (23.8 °C). In addition, we graphically assessed the beneficial effect of temperature rise in airborne pollen concentrations. We observed that the maximum pollen peaks over each MPS coincided with an increase in temperatures and the absence of precipitation (Figure 2). The relationship between the pollen air density and the vineyard yield resulted not statistically significant, but a trend to an increase of the yield with a high presence of vine pollen in the atmosphere was detected in our study.

Nevertheless, extreme high temperatures during flowering (>35 °C) have a detrimental effect on fruit set and final yield. High temperatures after budburst until fruit set leads to an advance of the phenology of berry set and have a negative effect on the number of flowers per inflorescence [44]. Many authors had demonstrated that high temperatures in a range of 35–40 °C around flowering are detrimental to fruit set and ovule fertility, which results in less berries per cluster [45,46]. Other studies pointed out that the negative effect of high temperature (around 35 °C) alters the soluble carbohydrate content in the pistil, which leads to the decrease of the pollen tube growth along the style and a reduction in fruit set [47]. The authors of [48] found a delay and a reduction of 50% in the rate of ripening, with a high incidence of berry shrivel and sunburn promoted by heat events with air temperatures of 40 °C. Consequently, heat events caused a significant reduction in berry quality. In our study area, daily maximum temperatures in July and August can reach 40 °C, being between 35 and 40 °C during some short periods. Important heat extreme temperatures events were detected in the second fortnight of July, which registered the maximum temperatures of the year (Figure 9) coinciding with the phenological stage of Development of fruits (BBCH-S7).

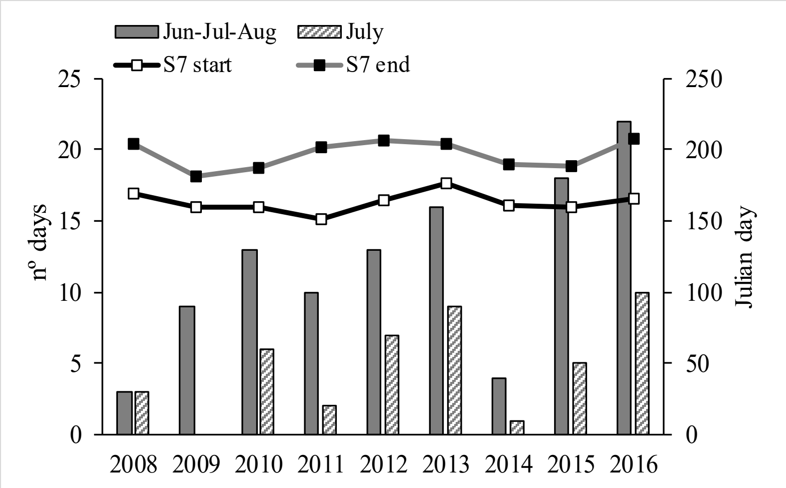

Figure 9. Number of days with daily maximum temperature >35 °C on each summer period (June–July–August), and during July, and Julian day of the fruit set phenological stage (S7) start and end date for each year.

The floral biology and the pollination process are also considered as fundamental factors for grapevine yield. Most of the commercial *Vitis vinifera* varieties used for wine and table grape production are plants with hermaphroditic flowers grouped in conical panicle-shaped inflorescences characterised by three levels of branching along the rachis and triplets of flowers [49]. The main pollination mechanism is the self-fertilisation [50], although cross-pollination also occurs with lower frequency, which improves seed set and fertilisation effectiveness [18]. This pollination trend for cultivated grapevine varieties was assessed for the Godello cv, since the detected airborne pollen concentrations in the present study were markedly lower in comparison with the calculated pollen grains produced per vines.

As aforementioned in Section 3.2, the formation of inflorescences, tertiary branches, flower and pollen per anther, similarly fluctuated among the considered years, with the exception of the years 2011, 2014 and 2017 (Figure 3). Nevertheless, the dissimilarities found in these years seem to soften the final pollen/vine production. This variable depends on the flower-pollen production balance. In the years with a flower decrease, 2014 and 2017, a marked increase in pollen/anther production was also registered, and as a result, the final pollen/vine increased. In 2011, the flower production increased and a marked descend in pollen/anther was also registered; consequently, the pollen/vine slightly decreased. This behaviour points out that vegetal pollen production is possibly auto-regulated as a function of the total flowers produced, in order to adjust the plant energy consumption. Furthermore, the general absence of significant correlations of the analysed flowering parameters with grape production could indicate that flowers and pollen are produced in a large excess, being compensated through the fruitset rate to keep a production adequate to the available conditions. In the case of Godello, previous studies regarding reproductive variables found high fruitset values (of 91.2%) for this variety, following the Alfrocheiro variety (97.4%) and the Siria variety (99.2%). All of them are old wine grape varieties of the Iberian Peninsula, and the common origin of Alfrocheiro and Godello denotes the important genetic contribution on the regulation of reproductive performance variables, since they are a descent of the Savagnin variety, also with a very high fruitset rate (90.8%) [51]

Previous studies analysing the morphological development of floral organs conducted in the same Ribeiro Designation of Origin area for Godello cultivar, noted an average pollen production per anther of 3169 pollen/anther for the period 2004–2008 [5]. This measure was similar to the average value found in this study for the period 2008–2017, of 3248 pollen/anther. The homogeneity on both results suggest that vines in this area are adapted to environmental conditions, showing a stable and regular pollen production over the different years despite the meteorological inter-annual variability. However, pollen production is affected by meteorological conditions, limiting the potential vegetal development capability. In addition to rainfall that washes pollen from the atmosphere, heat events during flowering can lead to temperature stress in vines, affecting pollen viability [50,52] or ovule fertility [46], which alters fruitset rate and final vine yield.

Our statistical results reflected the influence of meteorological conditions and morphological variables on the final grape production since the highest prediction ability was detected for the 11–20 July maximum Temperature, the 11–20 April Rain and the Inflorescences/vine. The detected high temperature events could explain the negative statistical influence of the 10–20 July maximum Temperature variable on grapevine yield found in the present study. High temperatures events during fruit set can decelerate berry growth and block sugar accumulation, which can produce important crop losses due to the reduction of berry development and the delay of ripening, compromising berry composition [53]. In addition, they could have a later impact on sugar accumulation in the ripening stage [54,55] due to heat events inhibitory effect on several sugar transporters and sucrose metabolic enzymes involved in sucrose loading to the berries [48]. Reductions in sugar accumulation in berries induced by high-temperature events have been related with a 35% reduction in photosynthesis over 12 days after high temperature events exposure [53], revealing that not enough carbon was available for berries to continue ripening during the heat event and several days later. The photosynthesis reduction induced by high temperatures is possibly related to carboxylation limitations and ribulose 1, 5-bisphosphate regeneration, since the activation state of the Rubisco enzyme is inhibited at high temperatures [48,56,57].

Despite the importance of autumn and winter rainfall for soil water refiling, which determines the initial values of the Fraction of Transpirable Soil Water (FTSW) considered as an indicator of the water status of the crop [58], abundant rainfall on different stages of grapevine development can have a detrimental effect on final yield. During the first spring grapevine phenological stages, rainfall can favour the development of fungal diseases, such as grey mould or downy mildew caused by *Botrytis cinerea* and *Plasmopara viticola,* respectively, which has a high destructive potential, and lead to important crop losses and a severe reduction of yield. This is consistent with the negative statistical influence of the 11–20 April Rain variable on the final grapevine yield found in the present study. A considerable correlation coefficient was registered between the accumulated rainfall of the second ten days of April and the concentrations of *Botrytis cinerea* spores in the 20 day pre-flowering period ($R = 0.609$; $p > 0.078$), which could be related to difficulties of an adequate fertilisation process. Many authors have related fungal disease levels at a given time with the airborne spore concentrations during previous periods, therefore airborne spore concentrations can be used as bio-indicators of pathogen development [59,60]. Rainfall can induce grey mould spread depending on their intensity, since light rainfall of approximately 2 mm may increase conidia dispersal because of the raindrops splash effect spreading the fungal infective structures to the leaves and other parts of the plants, increasing this mechanical dispersion with the raindrop size [61,62]. In spring, the fungal pathogens activate from their overwintering forms with optimum temperature and humidity conditions, which are variable depending on the pathogen. The optimum conditions for germination of *Botrytis cinerea* infective propagules by conidiophores formation and conidia development, which can be spread by rain or wind, are high relative humidity around 93% and temperatures from 20–25 °C [63,64]. Buds and young shoots including rudimentary inflorescences can be infected in early spring and before bloom by grey mould, leading to their desiccation and fall. Previous studies conducted in the same Ribeiro region also pointed out that high airborne *Plasmopara viticola* sporangia concentrations recorded during the phenological stage 5-BBCH (inflorescence emergence), corresponding to the end of the May period [65], reinforced the high infective potential during the pre-flowering period in the studied area hindering the fertilisation process.

The inflorescences per vine showed a positive influence on the final grape production. Previous studies indicated that the major influential factors on the final grapevine yield are environment, cultivar genotype and management techniques, focusing on the bunch number per vine as a determinant factor of yield [66]. Bunch number per vine, measured in the present study as the number of inflorescences per vine, explained the 58%–88% of seasonal variation in the [67] yield component analysis.

The obtained regression model showed a great adjust between the annual grape production (in kg/ha) and the forecast values, explaining the 98.9% of yield variability. In addition to this great prediction ability, this model offers a considerable time period of two months prior to harvest since yield forecast. Grapevine flowering in our study area usually takes place between May until mid-June, which lets us know the inflorescences' number at least two and a half months in advance to harvest. With this information and meteorological data of 11–20 April rain and 11–20 July maximum temperature, it is possible to predict grape production two months before, as harvest usually comes in about September.

5. Conclusions

A prediction model was developed for the Godello cultivar, one of the preferential autochthonous white cultivars in the Northwest Spain Ribeiro Designation of Origin vineyards, by means of aerobiological, meteorological and flower production analysis.

The present study showed the detrimental effect of rain for fertilisation during the flowering period, with a marked decrease in the airborne pollen concentrations. Additionally, we statistically corroborated the negative effect of high temperatures on fruit set and ripening that other authors previously reported. The pollen concentrations in the atmosphere of the vineyard were not statistically related to the grape yield.

The obtained multiple regression model explained the 98.93% of the variability of the data. It provided a fitted forecast as shown by the lineal regression analysis between observed and expected grape productions. The variability of crop productivity associated to climate change impacts can be taken into account with this model due to the consideration of the main meteorological variables with the highest influence on the final yield and its effect on the grapevine inflorescences production. This is possible due to the use by winegrowers of the obtained model, which offers two months in advance of the harvest forecast.

The proposed model represents a useful tool to achieve an adjusted crop yield prediction some months in advance, affording possible fraud detection due to the introduction of foreign grape, the optimisation of cultural and post-harvest tasks or the crop insurance hiring, which are essential aspects for the standardised quality of wines and products of the Ribeiro Designation of Origin area.

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