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3 Relationship between incidence and severity of peanut smut and its regional distribution in the main
4 growing region of Argentina

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17
18 Abstract

19 Peanut smut, caused by the soil-borne pathogen *Thecaphora frezii*, has increased in incidence in the main
20 Argentinian peanut-growing regions. Smut-affected pods transforms the kernel into a mass of teliospores, which
21 survive long-term in the soil. This study is the first large-scale (regional) survey to determine the occurrence and
22 distribution of peanut smut in the main growing area of Argentina. Surveys were conducted in Córdoba province,
23 in randomly selected commercial peanut fields (n = 217) grown from 2015 to 2020. A five-score severity scale
24 has been used to quantify the smut severity on pods (0 = healthy kernels and 4 = totally smutted kernels) and a
25 disease severity index (DSI) is calculated. Pods with severity scores of 3 and 4 are rejected by the industry and
26 produce a high volume of spores that spread among fields increasing the inoculum in the soil. Those pods were
27 classified as severely damaged pods (SDP). We evaluated the relative frequency of smut classes during the years
28 and established the relationships between the yearly incidence and DSI. The mean of the incidence was variable
29 (never zero) across the years and increased from 1.66% in 2015 to 11.47% in 2020. More than 80% of the affected
30 pods belonged to SDP group. The variable SDP, a more time and cost-effective method for quantifying peanut
31 smut, best explained the variation in DSI values. Our results suggest that that visual estimates of incidence and
32 SDP should be useful for disease monitoring, screening genotypes, or treatments comparisons in smut
33 management experiments. Our data update knowledge of the distribution of *T. frezii* in the peanut-growing area
34 of Argentina.

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36 Keywords: *Thecaphora frezii*, aggressiveness, peanut disease, linear regression

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38 **Introduction**

39 Peanut (*Arachis hypogaea* L.) is a high-value food crop cultivated worldwide. Its center of origin is the
40 northwestern Argentina and southeastern Bolivia (Hammons et al., 2016). Argentina produces high-quality
41 peanuts, mainly intended for export (approximately 90% of the production), with the European market being the
42 principal destination. More than 90% of Argentinian peanut production is concentrated in Córdoba province in
43 the central region of the country. Approximately 350,000 ha of peanuts are planted yearly and processed by the
44 industry established in the same region. The major peanut-producing departments are General Roca, Rio Cuarto,
45 and Presidente Roque Saenz Peña, located in the south of the province, with more than 65% of the total production
46 (Agüero, 2017; Calzada & Rozadilla, 2018).

47 Peanut smut, caused by *Thecaphora frezii* Carranza and Lindquist, is a soil-borne pathogen currently distributed
48 throughout Córdoba province (Paredes, 2017). The first record of the disease in Argentina dates from 1995, when
49 it was detected in Córdoba in the main peanut growing area (Marinelli et al., 1995). Since its detection, incidence
50 has constantly increased, reaching 100% prevalence since 2012 (Paredes, 2017; Rago et al., 2017). Infection
51 occurs when the peg is penetrating the soil, stimulating the germination of spores located in the soil and producing
52 local infection (Marinelli et al., 2008). Smut may completely transform the kernel into a mass of spores. Lesions
53 of smut lead to many spores that are released at harvest when the pods are broken. *T. frezii* spores survive for a
54 long time (several years) as teliospores in the soil (Cazón et al., 2016; Rago et al., 2017).

55 Many of the most popular peanut cultivars are smut-susceptible and continue to be widely planted. The
56 ‘Granoleico’ peanut cultivar (highly susceptible) is planted in more than 70% of cultivated areas in Argentina.
57 Breeding programs have been screening germplasm to evaluate both tolerance and resistance of different peanut
58 cultivars (Bennett et al., 2021; Bressano et al., 2019; Kearney et al., 2021; Wann et al., 2020). In recent years, one
59 new cultivar with high levels of resistance to smut infection was released. However, adoption by farmers is very
60 low due to several factors, such as seed multiplication to obtain sufficient quantities of commercial seed, low
61 yield, and other agronomic traits.

62 Variability is observed in smut symptoms, from a small sorus to the complete transformation of the kernel,
63 determining different classes of severity (Astiz Gasso et al., 2008; Rago et al., 2017). In some cases, hypertrophic
64 pods without signs of internal fungal presence have been observed (Bennett et al., 2021). Smut incidence is the

percentage of infected pods in a field sample. In addition, heavily affected pods are defined as class 3 and 4 (in a 0-4 severity class scale), where at least one or both kernels were transformed into a mass of spores, respectively (Paredes et al., 2021). A disease severity index, which takes the frequency of severity classes into account, is the most common measure of intensity of smut evaluated in surveys or field experiments (Rago et al., 2017).

Peanut smut caused significant losses to peanut production in recent years in the Argentinian peanut-producing region (Paredes, 2017; Rago et al., 2017). All fields in Córdoba province present *T. frezii* inoculum in the soil at different concentrations (spores per gram of soil), resulting in variable disease incidence, from less than 1% to more than 50%. Commercial peanut fields may be classified according to smut percent incidence: low (< 4%), medium (4 to 20%), or high (> 20%). Smut surveys in peanut-producing areas of Córdoba have shown a decrease in disease intensity from north to south (Paredes et al., 2016). This gradient is due to the fact that peanut processing factories are located principally in the north and are an important source of spore dispersal. During shelling, smutted kernels release teliospores that are dispersed by wind, increasing soil inoculum in nearby fields. In addition, new production areas are in the south of the Cordoba province where the history of peanut crops is shorter than in the north (Cazón et al., 2018; Paredes, 2017; Rago et al., 2017). Paredes (2017) reported peanut yield loss due to smut in the magnitude of 27,419 MT (US\$14,151,800), representing 3.15% of total production. The highest yield losses of 35% were estimated in highly infested fields (>50% incidence).

The quantification of severity (the degree of infection) is more laborious, but it best expresses the intensity of smut. This can be estimated visually with enhanced accuracy by means of a diagrammatic scale as an aid during the assessments (Bock et al., 2010). Due to the greater subjectivity in the estimates and the need for training or continuous use of a diagrammatic scale, severity has been seldom used compared to that of incidence, a much simpler, faster, and more objective method. Therefore, it is essential to increase knowledge about the epidemiological processes of peanut smut that can be useful for the improving the management of the disease. The aims of the present work were to: (i) evaluate the intensity of smut in the main peanut-growing area of Argentina; (ii) summarize the distribution of the classes of disease severity in pods; and (iii) model the relationship between incidence and severity classes.

Material and methods

Sampling sites and survey description

The survey was conducted in the main peanut cultivation area of Argentina (Córdoba province; Fig. 1). Commercial peanut fields were selected from 11 departments in Córdoba from the 2014–2015 to 2019–2020 growing season (herein, 2015 to 2020, the harvest year). Fields were sampled at random to be representative to survey in the extension of the peanut-growing area. The closeness of the shelling plants was not considered, and the same field was non-sampled more than once. All surveyed fields were grown under natural conditions (without water systems), with grower's standard management practices. Field size ranged from 80 to 400 ha. No peanut smut management strategies were applied in any of the sampled fields. The dose and timing of fungicide spraying for foliar diseases (leaf spot) have no effect on smut control (Paredes et al., 2021).

Fig. 1. Location of the main peanut cultivation area in Argentina. **A:** The dark gray area corresponds to Córdoba province where the main peanut-growing region and peanut processing industries are located. **B:** Departments surveyed in Córdoba province, where: RP: Río Primero; SM: Santa María; RS: Río Segundo; TA: Tercero Arriba; GSM: General San Martín; U: Unión; MJ: Marcos Juárez; JC: Juárez Celman; RC: Río Cuarto; PRSP: Presidente Roque Sáenz Peña; GR: General Roca.

All sampled fields are infested with inoculum of peanut smut since natural smut infections were observed in each field. Smut intensity was determined in the mature crop at approximately 140 day after planting at stage R8 (Boote,

1982; Rago et al., 2017). Disease assessments were performed by collecting all the plants in 1 m crop row at a pre-harvest stage (sampling unit/station). Samples were collected in a transect in the central area of the field, separated 50 m (at least) one each other. The number of samples ranged from 4 to 8, depending on the regional disease pressure according to Paredes et al. (2017). Four sample stations were enough for fields with high soil inoculum pressure (>8% incidence). Conversely, 8 samples were taken in fields with lower smut inoculum pressure (<4% incidence). All pods sampled at each station were evaluated.

Disease assessment and frequency of severity class

Peanut smut intensity was characterized by disease incidence (percentage of diseased pods out of the total of sampled pods) and severity (proportion of visibly damaged pod tissue). Smut severity was indirectly assessed using a five-class scale, in which the state of the individual pod damage was considered, wherein disease class ‘0’ = both kernels healthy; class ‘1’ = single kernel with a small sorus in a normal pod; class ‘2’ = half of the kernel affected in a deformed or normal pod; class ‘3’ = one completely smutted kernel in a deformed pod; and class ‘4’ = two completely smutted kernels in a deformed pod (Astiz Gasso et al., 2008; Rago et al., 2017). The disease severity index (DSI) was calculated according to equation 1. Arbitrary metrics were also obtained: i) Low Damaged Pods (LDP) included classes 1 and 2 as proportion of the total; and ii) Severely Damaged Pods (SDP) represented the proportion of classes 3 and 4 (Paredes et al., 2021). The distributions of disease severity classes were calculated as the severity class incidence (SCI) (2), expressed as a percentage of the total number of pods infected, and the relative frequency of disease severity classes (*f*DSC) (3):

$$DSI = (\Sigma (n \times \text{disease severity class}) / (N \times 4)) \times 100 \quad (1)$$

$$SCI_x (\%) = (n_x / N) \times 100 \quad (2)$$

$$fDSC_x = (n_x) / N_i \quad (3)$$

where N is the sample size, N_i is the total of infested pods in the sample, n is the number of pods corresponding to each disease severity class (0–4), and n_x is the number of pods corresponding to the x-th disease severity class.

Data analysis

The relationship between incidence (global and for each severity class) and DSI were analyzed by means of linear regression models. We considered that fields within a same location and year were not independent, so we grouped them into the same environment (i.d.). Then, we fitted mixed linear regression models to the data filtered by two conditions: environments (departments) with at least four sampled fields and a range of smut incidence of at least 5%. This restriction allowed us to estimate an id-level regression as a random effect and the overall line regression as a fixed effect. With $n = 20$ independent environments, the linear mixed model for environment i may be written as:

$$y_{ij} = (\beta_0 + u_{0i}) + (\beta_1 + u_{1i}) x_{ij} + e_{ij} \quad (4)$$

$$u_{0i} \sim N(0, \tau_{u0}^2); u_{1i} \sim N(0, \tau_{u1}^2); e_{ij} \sim N(0, \tau_e^2)$$

where y_{ij} smut incidence (field incidence or for each class incidence), x_{ij} a reference metric (SDI or field incidence, and e_{ij} the model residual, for the j th observation (field). β_0 and β_1 are the population average intercept and slope, respectively, whereas u_{0i} and u_{1i} are the environment-specific random effects on the intercept and the slope, respectively. The latter are considered normally distributed random variables with mean 0 and variances τ_{u0}^2 and τ_{u1}^2 , respectively. The error term, e_{ij} , is also considered to be normally distributed with mean 0 and residual variance τ_e^2 . The "lme" function from the "nlme" package was used to correct heteroscedasticity issues by the argument `weights = varPower(form = ~ incidence)`. Slopes of the regression line were used to compare the severity class incidence. All data were analyzed in R version 3.5.1 (Team R Development Core, 2018).

Results

Peanut smut survey data

From 2015 to 2020, 217 fields in Cordoba province were surveyed. Department surveys corresponded to the main peanut-growing region of Cordoba, Argentina (Fig. 2, Table 1). A total of 130 fields (60% of surveyed fields) were collected in Rio Cuarto, General Roca and Presidente Roque Saenz Peña (most productive areas); 24, 22.6, and 13.4% of the fields were collected in those departments respectively. In addition, 40% of fields were surveyed in 2020, with a high volume of data in that year (87 fields).

Fig. 2. Yearly maps (2015 to 2020) of peanut smut survey of 217 commercial peanut fields in 11 departments in the main peanut-growing area in Córdoba province, Argentina.

Agronomic conditions of the crops varied among the years for edaphic factors or environmental variations. Accumulated rainfall recorded during the peanut cropping season (November to April) is presented in supplementary table (ST 1). In 2017, there was a severe drought (300 mm less than normal) during the growing season.

Table 2 summarizes data on disease incidence (DI) and DSI for the collected fields through years. Based on the samples in this study, from 2015 to 2020, no field with 0% incidence was recorded in Córdoba province. The mean of the incidence increased from 1.66% in 2015 to 11.47% in 2020. In general, smut severity index (0.01 to >35%) and incidence (0.04 to >40%) varied considerably within the same year, with exception of years 2015 and 2019 (Fig. 3). Out of the 217 fields sampled, 97 fields (44.7%) showed a low intensity (DI < 4%; DSI < 3), 89 fields (41%) showed medium intensity (DI > 4 to < 20%; DSI > 2.3 to < 15.4), and 31 fields (14.3%) showed a high intensity (DI > 20%; DSI > 15).

Fig. 3. Distribution of peanut smut severity index and incidence surveyed from 2015 to 2020 in Córdoba, Argentina. The vertical red and grey lines represent the median and maximum values, respectively for each year.

With exception of years 2015 and 2019, both disease metrics presented a right skewed distribution, with more than 50% of values lower than 10%. This difference in the shape of the distribution between 2015 and 2019 with the other years can be due to the low number of fields included in the survey ($n = 7$ and $n = 14$, respectively; Table 1). Despite the lower number of assessed fields, both median values of DSI and incidence were similar to the other years with higher totals of assessed fields. Median values of both smut intensity metrics consistently increased from 2015 to 2020 with a higher increment of smut incidence (+6.6 folds) than smut severity index (+5.4 folds). This differential relative change of both metrics can be explained by the decrease of smut severity class 4 in contrast to an increase of smut severity class 1 along the period of study (Figure 4). Even with this variation of disease severity class, frequency class 3 represented 41 to 47% of the total diseased pods, followed by class 4, with a frequency ranging from 28 to 44% over all surveyed years. In any of the years of survey, both class 3 and 4 represented at least 75% of diseased pods (year 2019). In contrast, classes 1 and 2 showed the lowest frequency over the surveyed years (mean 13.36 and 11%, respectively).

Fig. 4. A: Box plots showing the distribution of the relative frequency in disease severity classes for peanut smut in fields surveyed from 2015 to 2020. The solid line in the box represents the median, the white dots the mean, the upper and lower limits of the boxes represent the 25th and 75th percentiles of the data, respectively, and the black dots represent outliers. **B:** Stacked bar represents the mean of the relative frequency in disease severity classes for peanut smut in fields surveyed from 2015 to 2020.

Relationships analysis of smut intensity metrics

The linear regression provided good enough to assess the relationship between smut intensity metrics (see model diagnostic plots in Fig. S1). A wide range of smut data were used for the analysis, 74 fields grouped in 20 environments (field location department x year). From the decomposed analysis of each severity class incidence against field incidence, we observed that the best representation of disease incidence was by disease severity classes 3 and 4 as SDP ($\beta_1 = 0.45$ and 0.35 , respectively; $P < 0.001$). The lowest slopes were observed in severity classes from LDP, 0.061 and 0.095 for severity classes 1 and 2, respectively (RMSE = 0.736 and 0.508 , respectively; $P < 0.001$). We also included in the analysis the incidence of SDP and obtained a $\beta_1 = 0.81$ ($P < 0.001$, RMSE = 0.392).

Fig. 5. Regression lines for relationships between severity class incidence and incidence of peanut smut in fields surveyed from 2015 to 2020 in Córdoba, Argentina. Solid grey lines represent the study-specific relationships, the solid blue line represents the linear regression, and the grey shade area represents the 95% confidence interval.

Finally, we evaluated the relationship between disease incidence or SDP incidence and the DSI (Fig. 6). Smut incidence increased along the DSI values as a linear rate of 1.291. SPD incidence had the closest relationship with SPD incidence ($\beta_1 = 1.054$, $RMSE = 0,392$).

Fig. 6. Linear regression of the disease incidence (left) and severely damaged pods (SDP) (right) as a function of disease severity index (DSI) of peanut smut in fields surveyed from 2015 to 2020 in Córdoba, Argentina. Solid grey lines represent the study-specific relationships, the solid blue line represents the linear regression, and the grey shade area represents the 95% confidence interval.

Discussion

Since the first report of peanut smut in commercial peanuts in 1995, the disease incidence and prevalence have gradually increased in the main peanut-growing region of Argentina (Asinari et al., 2019; Marinelli et al., 2010; Paredes et al., 2016; Rago et al., 2017). Based on the results of this study, in the last five years (2015–2020), peanut smut incidence and DSI increased from 1.67 to 11.47% and from 1.36 to 8.73, respectively. Future increases are expected due to the lack of management practices adoption for controlling smut (Rago et al., 2017). In this study, the important areas for peanut cultivation in Córdoba were surveyed to assess the current impact of smut, representing the principal peanut production area in the country. Although more than 90% of total production is concentrated in Córdoba, peanuts are present in other provinces, such as Salta, San Luis, La Pampa, and Buenos Aires (Calzada & Rozadilla, 2018). However, these areas are small, cultivation is inconsistent, and were considered negligible, not representative, or with minor importance on peanut cultivation in Argentina. To the best of our knowledge, this is the first analysis of the intensity of peanut smut in Córdoba province.

Among the reasons for the increase in disease intensity is the lack of clear management strategies for control the disease, and the poor cultivar diversification in planting areas (Rago et al., 2017). Regarding genetic resistance,

few commercial cultivars with tolerance to smut have been registered in recent years [EC – 191 RC (AO), RESOL-2019-108-APN-INASE#MAGYP; MA-757 (INASE Reg. No. 17240)] (Oddino et al., 2013; Wann et al., 2020). The area occupied by those varieties is not significant in relation to that currently cultivated with the most predominant variety. The challenge for breeding programs is to identify resistance genes in wild and cultivated germplasm to breed for high-yielding resistant cultivars and reduce teliospore production and delay the spread of smut (Bennett et al., 2021; Bressano et al., 2019; De Blas et al., 2019; Rago et al., 2017; Wann et al., 2020). In this survey, all samples were collected from commercial cultivars without tolerance to smut; our results indicate that the intensity and the analysis in this study is associated with susceptible host cultivars. However, genetic variation in pathogens may differentiate the variability in aggressiveness (Pariaud et al., 2009). The degree of genetic variability of *T. frezii* is not currently well documented, though phenotypic variability in its virulence is present.

Fungicide applications are not used to control smut due to their relative low efficacy. The target (soil and pegs) is difficult to reach because of plant architecture at the pegging stage (Augusto et al., 2010; Cazón et al., 2018; Paredes et al., 2021). Our observations were based on a limited number of fields and did not consider chemical protection for other diseases. However, the most common fungicide programs to control peanut diseases in crops (i.e., chlorothalonil to leaf spot) do not have smut control (Camiletti et al., 2021; Paredes et al., 2021; Rago et al., 2017).

In general, it is considered that the active movement of most soilborne pathogens in soils is very limited (Katan, 2017). Nevertheless, the spread of smut to other fields or regions is remarkable, indicating that they have effective means for dispersal. The most effective way to spread soil-borne pathogens is by means of infected plant propagation material, e.g., seeds, tubers, transplants, and cuttings. However, other means of pathogen dispersal are via infested soil, or by being carried by agricultural tools and machines, water, and wind (Rekah et al., 1999). In Argentina, the increase in disease intensity and prevalence occurred in a relatively short period. Smut spores are commonly spread into disease-free fields through infested seeds (Cazón, 2015; Rago et al., 2017). The determinant of reaching a 100% prevalence in the producing area was related to peanut companies that process commercial peanuts and peanut seeds in the same processing industries (Rago et al., 2017).

Polyetic characteristics of the disease (annual inoculum accumulation in the field in subsequent seasons) added to the survival capacity of spores in the soil, increased the disease incidence and prevalence. According to published studies, the spores can remain infective for more than 4 years in contaminated soils (Cazón et al., 2016). As we

observed in this analysis, SDP represents the major infection in smut, and these severity classes were the most important in spore production. The intensity of smut symptoms (SDP) had an impact on the inoculum increase, as they were lost at harvest (Paredes et al., 2017). The major mechanism of inoculum spread is spore liberation from broken infected pods during the harvesting process since many spores can be dispersed by wind. Disease management programs must consider the easy spread of inoculum over short distances (Rago et al., 2017). In addition, most peanut processing factories are located in the same growing region (Agüero, 2017). Smutted pods may be carried to the industries and broken during the peanut processing. This leads to a high volume of spores that may be dispersed and accumulated in local fields around factories. This is confirmed by the highest incidence near these industries. In addition, regional incidence where industries were established leads to the highest values of incidence (i.e., Tercero Arriba and Juárez Celman).

The broken infested pods and the mobilization of soil in the harvest process might lead to a homogeneous distribution of spores in the soil. Levels of inoculum in the soil are widespread in Córdoba province, according to the incidence recorded in different surveys (Asinari et al., 2019; Cazón et al., 2018; Paredes, 2017). Fiers et al. (2012) indicated that for potato soilborne pathogens, there is not always a clear and linear relationship; the severity of the disease generally increases with an increasing level of inoculum. Sometimes, a minimum inoculum threshold is needed to initiate disease development. Although the incidence of smut is dependent on the soil inoculum in the soil (Paredes et al., 2019), our results showed that this variable does not affect the intensity of symptoms, as confirmed by the frequency of severity classes, which did not differ between levels of incidence.

In some pathosystems, severity is more difficult to assess, but it more accurately estimates intensity, especially in foliar disease (Marcuzzo & Carvalho, 2017). The levels of the severity scale of smut are well-differentiated. However, more dispersion of data was observed in class 1, when symptoms were more difficult to discern. The same result was observed by Bennett et al. (2021), who observed that errors in measuring incidence were most likely to occur when severity was low (i.e., small solitary sorus was more likely to be missed). In many plant pathogens, there is a widespread tendency to overestimate disease severity at low severities (<10%) (Bock et al., 2010).

A strong relationship between disease severity and incidence was observed in the current study. This finding confirms and is consistent with results by other researchers, with a strong and significant positive correlation between incidence and severity (Bennett et al., 2021; Kearney et al., 2021; Marraro Acuña et al., 2014). A strong correlation between incidence and severity allows for screening germplasms by only recording incidence (Seem,

1984). However, new futures genotypes may have a greater resistance, based on preventing further colonization or symptom development, in which case incidence could continue to grow with less severe symptoms. A fit in the relationship could be necessary in that case. At present, Marraro Acuña et al. (2014) screened the intensity of smut from 10 genotypes and concluded that for peanut smut, incidence data were sufficient for resistance screening. In accordance, Bennett et al. (2021) suggested an alternative phenotyping approach that relies solely on rating pods for disease incidence. In addition, the slope of the line indicates the importance of each degree of severity in the incidence of the disease. SDP represents more than 80% of infections, which demonstrates how aggressive peanut smut can be. In addition, classes 3 and 4 represent the greatest impact on yield loss, the kernels have completely smutted and had less quality in the peanut industry. The relationship between incidence and severity may also be compared with yield loss. Paredes (2017) showed a significant linear relationship between estimated yield losses and disease intensity.

Water limitation and drought stress conditions might influence the infection and severity of diseases (Kambiranda et al., 2011). Increases in susceptibility or tolerance depends on the interaction and specific pathogen. In the case of cyst nematode, the relationship between inoculum density and disease severity greatly depends on the environmental factors that determine the level of soil suppressiveness (Fiers et al., 2012). Based on our experience, peanut smut had an increased incidence when less precipitation was accumulated during the pegging phenological stage (January to March), due to water stress periods (Paredes, *unpublished*). However, no differences were observed in the frequency of severity classes of smut in this study.

Diseases caused by soilborne pathogens cause heavy losses to many crops (Katan, 2017). In many cases, they are destructive and of high economic importance. Potato smut (*Thecaphora solani*) is one of the most destructive fungal diseases affecting potato. In the northern part of Chile, this disease is established in many soils, causing significant yield losses that often exceed 90% (Andrade et al., 2004). Peanut smut had a remarkable increase in disease incidence over the years (Asinari et al., 2019). In 2016, fields with high disease levels were commonly located in the center of the province, near processing factories (Rago et al., 2017). However, in the last two years a considerable increase in disease incidence was also observed in the south of the province. In other soil-borne pathogens, *Synchytrium endobioticum* in potato is considered a highly destructive disease and may cause 100% loss of potential tuber yield (Wale et al., 2011). Conversely, in peanut smut 100% incidence has never been registered, even in experimental situations with high volume of spores in the soil (>15,000 teliospores/g of soil).

However, the potential yield losses may increase over time. In highly infested fields, yield loss was estimated at 35% with >50% incidence (Paredes, 2017).

In conclusion, data from the present study provided relevant information on the relationship between incidence and severity of smut. Peanut smut is highly aggressive, with an infected pod likely having a high disease severity, as confirmed by the close relationship between severity classes and incidence. The disease was not considered a serious threat for peanut cultivation at its re-emergence in 2006. Diverse factors have likely contributed to spread the disease within Córdoba province, making this disease the most serious phytopathological problem for peanut growers. The principal factor to increase spores in the soil is the production of spores due to the aggressiveness of smut result in a high spore production in the soil, with the subsequent spread among fields. This led to an increase of disease incidence in the main peanut-growing area. The results obtained in this work contribute to progress in the knowledge of the distribution of *T. frezii* in the main peanut-growing area of Argentina. In addition, we suggest assessing the disease by severely damaged pods (SDP). According to the data obtained, the incidence of SDP had the best representation of DSI, which is a faster method of quantifying peanut smut. SPD and incidence can be adopted for monitoring purposes, screening genotypes in breeding programs, or treatments comparisons in smut management experiments.

Authors' contributions

Juan Andres Paredes: Conceptualization, methodology, formal analysis and investigation, and writing

Juan Pablo Edwards Molina: Validation, formal analysis, visualization, and writing

Luis Ignacio Cazón: Writing methodology

Florencia Asinari: Data Curation

Joaquin Humberto Monguillot: Data collection

Sergio Alejandro Morichetti: Resources provision

Alejandro Mario Rago: Project administration

Adriana Mabel Torres: Supervision and writing

Data availability statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics declarations

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest. All authors gave approval for submission of this manuscript. The authors declare that no conflicts of interest exist.

Disclosures and declarations

The manuscript has been prepared following principles of ethical and professional conduct. The research did not involve human participants or animals. Therefore, neither statements concerning informed consent nor welfare of animals is applicable.

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Table 1. Number of fields surveyed for peanut smut from 2015 to 2020 in different departments of Cordoba province, Argentina. Mean of smut incidence (%) and disease severity index (DSI) according to department and year and the highest and lowest values for each field were summarized.

Department	2015					2016					2017					2018					2019					2020					Total of fields
	Incidence		DSI			Incidence		DSI			Incidence		DSI			Incidence		DSI			Incidence		DSI								
	n	mean	min	mean	min	n	mean	min	mean	min	n	mean	min	mean	min	n	mean	min	mean	min	n	mean	min	mean	min						
			max		max			max		max			max		max			max		max			max		max						
General Roca	1	1.56	1.56	1.38	1.38	11	2.54	0.38	1.87	0.27	14	2.82	0.63	2.18	0.45	6	4.06	1.22	2.82	0.87	2	1.13	0.91	0.74	0.59	18	13.41	1.17	10.32	0.64	52
			1.56		1.38			12.16		9.24			9.19		7.43			7.29		4.94			1.35		0.88			36.09		29.7	
General San Martín						2	5.82	2.83	4.43	2.07	4	7.14	2.09	5.60	1.54	5	17.38	2.96	14.27	2.22						5	3.84	1.88	2.78	1.44	16
								8.81		6.79			13.41		10.53			41.23		35.83								6.22		4.87	
Juarez Celman	1	1.23	1.23	1.01	1.01	4	25.58	5.76	20.32	4.49	9	16.92	2	13.63	1.64	6	8.85	2.12	7.26	1.72						13	10.76	1.07	7.60	0.77	33
			1.23		1.01			55.21		45.21			37.26		31.14			12.48		10.34								23.06		18.41	
Marcos Juarez																										2	0.16	0.04	0.05	0.01	2
																												0.29		0.09	
Pte. Rque Saenz Peña	2	3.6	2.86	2.95	2.37	4	3.21	0.85	2.39	0.65	4	1.07	0.64	0.74	0.53	2	3.1	1.43	2.22	1.02	3	5.61	3.93	3.53	1.86	14	10.68	0.24	8.27	0.09	29
			4.34		3.53			4.63		3.5			1.61		1.09			4.78		3.41			8.05		5.97			38.06		31.32	
Rio Cuarto	3	0.54	0.43	0.42	0.3	7	4.19	0.43	3.06	0.28	10	2.83	0.6	2.07	0.4	5	4.9	0.44	3.54	0.36	6	9.62	2.6	6.92	1.73	18	14.91	1.85	11.59	1.26	49
			0.7		0.57			13.23		9.37			5.83		4.41			13.65		8.94			17.41		13.13			47.84		36.91	
Rio Primero																										2	13.74	7.89	9.75	5.38	2
																												19.59		14.13	
Rio Segundo						1	20.73	20.73	16.93	16.93	1	1.39	1.39	0.79	0.79											3	6.4	4.36	4.88	3.29	5
																												9.96		7.69	
Santa Maria																										1	5.03	5.03	3.10	3.1	1
																														3.1	
Tercero Arriba						3	15.64	1.92	12.46	1.49	4	28.45	14.67	23.35	12.17	5	12.95	2.6	10.16	2.01	3	15.84	13.29	12.25	10.39	5	22.73	14.31	17.83	11.48	20
								39.33		31.84			46.13		37.61			28.77		23.11			20.21		15.45			47.1		34.74	
Unión																2	0.65	0.12	0.33	0.09						6	2.31	0.23	1.74	0.16	8
																		1.19		0.57								9.15		6.83	
Total of fields	7					32					46				31						14					87					217

Table 2. Descriptive statistics for peanut smut disease incidence and disease severity index (DSI) in fields surveyed from 2015 to 2020.

Year	n of fields	Incidence (%)					DSI				
		Mean	SD	CV	min	max	Mean	SD	CV	min	max
2015	7	1.66	1.45	87.11	0.43	4.34	1.36	1.19	87.55	0.3	3.53
2016	32	7.87	12.12	154.06	0.38	55.21	6.12	9.84	160.73	0.27	45.21
2017	46	8	11.15	139.3	0.6	46.13	6.38	9.23	144.64	0.4	37.61
2018	31	8.42	9.23	109.55	0.12	41.23	6.63	7.79	117.57	0.09	35.83
2019	14	8.88	6.36	71.66	0.91	20.21	6.45	5.03	77.99	0.59	15.45
2020	87	11.47	11.06	96.39	0.04	47.84	8.73	8.7	99.56	0.01	36.91

Fig. S1. Data filtering criterion for the random coefficient regression analysis: environments composed by the interaction of the field location and year of sampling with at least 4 fields and a range of smut incidence of 5% were kept for modeling purposes.

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ST 1. Accumulated precipitation registered (mm) during the peanut cropping season (November to April) in the growing season surveyed (2014-15 to 2019-20)

2014-15							2015-16							2016-17							
Department	Nov	Dec	Jan	Feb	Mar	Apr	Acumulated	Nov	Dec	Jan	Feb	Mar	Apr	Acumulated	Nov	Dec	Jan	Feb	Mar	Apr	Acumulated
General Roca	61	102	124	139	56	80	561	179	89	259	97	32	113	769	44	106	98	76	194	120	638
Gral. San Martín	80	94	148	275	191	48	836	172	112	132	264	51	134	865	22	114	103	125	81	79	523
Juárez Celman	93	100	76	243	119	90	720	158	98	155	198	67	101	777	20	64	114	116	73	86	473
Marcos Juárez	112	132	116	145	169	101	775	175	105	152	187	67	111	797	36	94	128	81	111	131	580
Pte. Roq. Sáenz Peña	79	132	144	147	127	98	726	115	137	279	115	68	74	787	49	146	153	102	152	136	738
Río Cuarto	110	98	82	251	127	52	719	180	112	168	143	91	96	790	31	75	118	79	101	85	489
Río Primero	79	98	139	333	125	46	819	78	75	66	177	84	123	603	74	88	111	163	51	41	527
Río Segundo	101	97	160	278	134	37	807	121	85	99	239	79	174	797	50	133	119	136	63	80	582
Tercero Arriba	75	101	155	185	163	47	726	123	82	125	275	65	138	808	37	91	89	133	81	50	481
Unión	99	99	146	246	185	64	839	138	111	138	201	63	113	764	22	111	105	125	82	102	547
Total							753							776							558

2017-18							2018-19							2019-20							
Department	Nov	Dec	Jan	Feb	Mar	Apr	Acumulated	Nov	Dec	Jan	Feb	Mar	Apr	Acumulated	Nov	Dec	Jan	Feb	Mar	Apr	Acumulated
General Roca	70	75	60	9	10	44	268	128	58	128	48	53	53	469	86	92	130	38	156	45	547
Gral. San Martín	43	152	36	6	18	118	373	249	148	119	23	160	93	791	54	111	125	120	98	18	526
Juárez Celman	73	141	51	9	16	114	404	185	112	169	29	137	77	709	75	138	107	149	135	15	618
Marcos Juárez	14	160	64	7	14	159	418	177	142	201	31	116	116	783	76	160	124	168	129	53	711
Pte. Roq. Sáenz Peña	93	90	104	11	38	72	408	62	94	159	24	78	50	467	63	149	154	121	205	48	739
Río Cuarto	27	109	95	32	15	61	339	153	72	163	30	173	55	646	99	79	95	125	142	35	574
Río Primero	66	101	80	30	5	36	318	95	66	230	50	128	145	714	130	111	63	172	69	28	573
Río Segundo	22	123	91	43	6	57	342	144	76	199	65	126	126	736	87	149	37	150	97	21	540
Tercero Arriba	63	137	91	44	15	82	432	205	78	212	50	245	130	920	43	93	62	125	115	29	467
Unión	65	166	60	5	11	135	442	216	138	183	45	125	83	790	68	136	120	148	120	32	625
Total							375							703							592

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