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Global risk levels for corn rusts (*Puccinia sorghi* and *Puccinia polysora*) under climate change projections

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Abstract

Common rust (*Puccinia sorghi*) and southern rust (*Puccinia polysora*) are two of the most important foliar corn diseases worldwide. These fungi have caused severe economic loss to corn yields worldwide. The current and future potential distribution of these diseases was modelled with CLIMEX using the known current geographic locations of the rusts, growth and stress indices. The models were run under the A2 scenario using CSIRO-Mk3·0 and MIROC-H for 2050 and 2100. The current projection shows areas with marginal to optimal suitability in all the continents. The models for future projections display a general reduction in the Southern hemisphere and increase in the Northern hemisphere, especially for the southern rust. The overlay of the General Circulation Models produce an estimation of the common areas under risk for future climate conditions for the simultaneous occurrence for both corn rusts, with a reduction of the medium- and high-risk categories by 2100. This study highlights the possible effects of climate change at a global level for common and southern rust, as well as the risk of occurrence of both diseases in common areas for future climate that could be particularly harmful for crops.

KEYWORDS

CLIMEX, common rust, dry stress, heat stress, southern rust

1 | INTRODUCTION

Corn is the third most important cereal grown for human consumption. Common rust (*Puccinia sorghi*) and southern rust (*Puccinia polysora)* are two of the most important fungal diseases of corn (Roelfs & Bushnell, 1985). There are important differences between these corn rusts. Common rust occurs throughout corn production areas, coexisting with the crop. It predominates at higher elevations and under lower temperatures but can also be found in tropical areas. Its pustules appear on the upper and lower leaf surfaces and are characterized by an elongated shape and are brown to brown-red colour. Southern rust is more common at higher temperatures. Its distribution is tropical to subtropical; however, under favourable conditions, it can spread to temperate regions. Its orange-red to light brown round-shaped uredia appear on the upper leaf surface (Crouch & Szabo, 2011; Pavgi, 1972; Roelfs & Bushnell, 1985).

If the weather conditions are favourable for survival, increase and spread, common rusts can cause substantial yield loss, especially in sweet corn and corn for seed production. Currently, there is an absence of data regarding economic losses due to the corn rusts; however, in Minnesota, USA, a minimum economic loss of 3 million US dollars was estimated due to common rust in sweet corn in 1977, and in Georgia, USA, southern rust caused a damage of more than 18 million dollars in 2014 (Groth, Zeyen, Davis, & Christ, 1983; Little, 2014).

Common rust generally fails to impact economically; however, important epidemics have occurred. In susceptible corn varieties occurring in temperate areas, common rust can cause severe epidemics, causing losses of between 10% and 75% of corn yields (Dey et al., 2012; Groth et al., 1983; Pataky, 1987; Roelfs & Bushnell, 1985). Common rust also damages corn ears, plant weight and height, as well as the oil and protein content, thus reducing the overall quality of the crop (Groth et al., 1983; Roelfs & Bushnell, 1985). Experimental studies have estimated that with every 10% increase in rust severity a yield loss between 2% and 7% occurred in sweet corn varieties (Pataky, 1987; Shah & Dillard, 2006).

Southern rust appears to have a greater potential to damage crops. It can be a serious disease in warm-hot humid areas, unless it is managed. The occurrence of the disease in late-season planting can affect the flowering time and cause the death of the plant (Futrell, 1975; Rodriguez-Ardon, Scott, & King, 1980). An increase in the disease occurrence has been reported in recent years in the USA, which may be related to an increase in host availability (Crouch & Szabo, 2011). Epidemics have occurred in the USA and in West Africa (Futrell, 1975; Rhind, Waterston, & Deighton, 1952).

In crops, fungal and bacterial diseases are mainly dependent on the availability of a susceptible host, but climate is also a key determinant influencing the pathogens' rate of growth, infection and dissemination (Godoy et al., 2003; Pavgi & Dickson, 1961). In the cereal rusts, temperature and humidity are the major determining factors for spore germination, penetration, establishment and spread of the disease (Pavgi, 1972). Signs of increased disease has been noted in agricultural crop production influenced by the environmental and changing climate conditions (Altizer, Ostfeld, Johnson, Kutz, & Harvell, 2013; Evans, Baierl, Semenov, Gladders, & Fitt, 2008). For example, it has been predicted that plant disease epidemics will increase and move poleward (Bebber, Ramotowski, & Gurr, 2013). Additionally, climate change may alter host–pathogen interactions, changing the development and cycle, host resistance or susceptibility, and increasing transmission rates (Altizer et al., 2013; Evans et al., 2008).

Models such as CLIMEX that predict the effect of climate change on species distribution may be used to project the future potential distribution of plant diseases caused by pathogens. CLIMEX has been used to predict the potential geographic distribution of *Fusarium oxysporum* in date palm production; *Pyrenophora semeniperda*, the causal agent of leaf spotting in annual and perennial grasses; dothistroma needle blight which is caused by *Dothistroma septosporum*; *Dothistroma pini*, a pathogen which infects over 70 pine species; *Puccinia psidii*, which affects plant species in the family Myrtaceae; and other plant pathogens (Kriticos, Morin, Leriche, Anderson, & Caley, 2013; Watt, Kriticos, Alcaraz, Brown, & Leriche, 2009; Yonow, Kriticos, & Medd, 2004).

The objective of this study was to model the potential suitable and unsuitable areas under current and future climate for common rust (*P. sorghi*) and southern rust (*P. polysora*) using CLIMEX, based on climatic suitability and recorded geographic distribution of these corn rusts. Additionally, common areas for the two corn rusts were identified, to highlight the areas under greater risk for corn cultivation.

2 | MATERIALS AND METHODS

2.1 | CLIMEX description

CLIMEX is a process-based model that assumes that a population has two different seasons, a favourable season where the population experiences positive growth (Annual growth index, GI_A), and an unfavourable season where the population experiences negative growth (stress indices). The GI_A incorporates the temperature index (TI) and the moisture index (MI). Stress interactions are measured by four stress indices: cold, heat, dry and wet, as well as their interactions. The growth parameters are linked to the presence of the organism, whereas stress parameters are linked to the abundance of the organism (Sutherst, Maywald, & Kriticos, 2007). In the case of plant diseases, such as the rusts, the presence of the organisms is linked with the presence of a suitable host and the abundance and spread under favourable climate conditions (Watt et al., 2009). The growth and stress indices (SI) are multiplied to calculate the Ecoclimatic Index (EI) that shows the overall annual climatic suitability of the population ($EI = GI_A \times SI$). CLIMEX indices are calculated on a weekly basis and afterwards an annual value is obtained. The EI ranges from 0 to 100, where a value of 0 denotes a region where the population is unable to persist and a value of 100 denotes a region where ideal climatic conditions for the population persist (Sutherst & Maywald, 1985). For a more detailed explanation of CLIMEX model, please refer to Sutherst et al. (2007) and Kriticos et al. (2015). In this study, the classification of the EI was EI = 0 = not suitable, a region where the population do not persist; EI = 1–10 = marginal, where the population has limited conditions to persist; EI = 10–20 = medium, where the region can support large populations, and EI>20 = optimal, where the population has highly favourable conditions to persist. These categories are recommended by the CLIMEX manual and other CLIMEX studies (Kriticos et al., 2015; Sutherst & Maywald, 1985).

2.2 | Global circulation models and climatic scenarios

In this study, only the A2 SRES scenario was used because this emission scenario is the most probable with the actual CO_2 emissions and with the current population growth trend. Other scenarios are more conservative and underestimate trends of increase in temperature, sea level and greenhouse gases emissions (Raupach et al., 2007). The current and potential distribution was modelled using two General Circulation Models (GCMs): CSIRO Mk3·0 and MIROC-H for future potential distributions for the periods 2050 and 2100. The CliMond 10′ gridded resolution data were downloaded in CLIMEX format, containing average monthly maximum and minimum temperatures, average monthly precipitation and relative humidity at 9:00 and 15:00 hr; these parameters were used to project the climatic suitability for 2050 and 2100. The historical suitability was modelled with the CliMond 10′ baseline data, averaging the period 1961–1990 (Kriticos et al., 2011).

2.3 | The known distribution of common and southern rust

The known native and exotic geographic distribution data were used to develop the current and future global distributions of the corn rusts. The data were gathered from the Global Biodiversity Information Facility (GBIF 2017), the Atlas of Living Australia (ALA 2014), the PlantWise (PlantWise 2015), as well as literature resources (Cammack, 1958; Moratelli et al., 2015; Raid, Pennypacker, & Stevenson, 1988; Schieber, Rodriguez, & Fuentes, 1964). A total of 179 records for common rust, and 102 records for southern rust were collected to model and validate the CLIMEX model projections.

Known distribution records of common rust for Africa (19 records) and of southern rust for the Southeast Asian region (17 records) were set aside and not used for the modelling process, but were used to validate the final model fitting (Figure 1). At no time were the validation points overlaid on the maps during the model building phase. The geographic coordinates of *P. sorghi* and *P. polysora* are listed in Table S1. It is important to mention that CLIMEX works on present data only.

2.4 | Fitting CLIMEX parameters

CLIMEX parameter fitting was performed via visual inference from the known geographic distribution of the species. Growth and stress parameters were manually fine-tuned by an interactive method, until these reached agreement with the known distribution, as described by Sutherst et al. (2007). Stress parameters were initially adjusted to limit the pathogens to survive beyond their known distribution (core distribution). Thereafter, growth and moisture parameters were adjusted. For the fitting of growth parameters, available values from data experiments were used, where possible. Stress values were inferred from the distribution data. Every parameter value was justified for future reference. To allow for the expansion of the fundamental niche beyond the native constraints, all known records were used (Sutherst, 2003). The values that provided the best fit to the observed distribution are listed in Table 1. Refer to Table S2 for references used to fit the parameters.

2.5 | Cold stress

CLIMEX has three different methods to calculate the cold stress. For this study, two methods were used. The cold stress temperature threshold (TTCS) and its accumulation rate (THCS) were used to limit the spread of common rust to Canada, north of the USA, Patagonia, the Nordic countries and Russia, where no records of this rust have been found to date. This method limits the survival of the species if it is exposed to low temperatures. Common rust infection is not tolerant to cold; urediniospores cannot survive winters in England (Mahindapala, 1978b; Revilla, Hotchkiss, & Tracy, 2003). The minimum temperature reported for urediniospores germination is 4°C

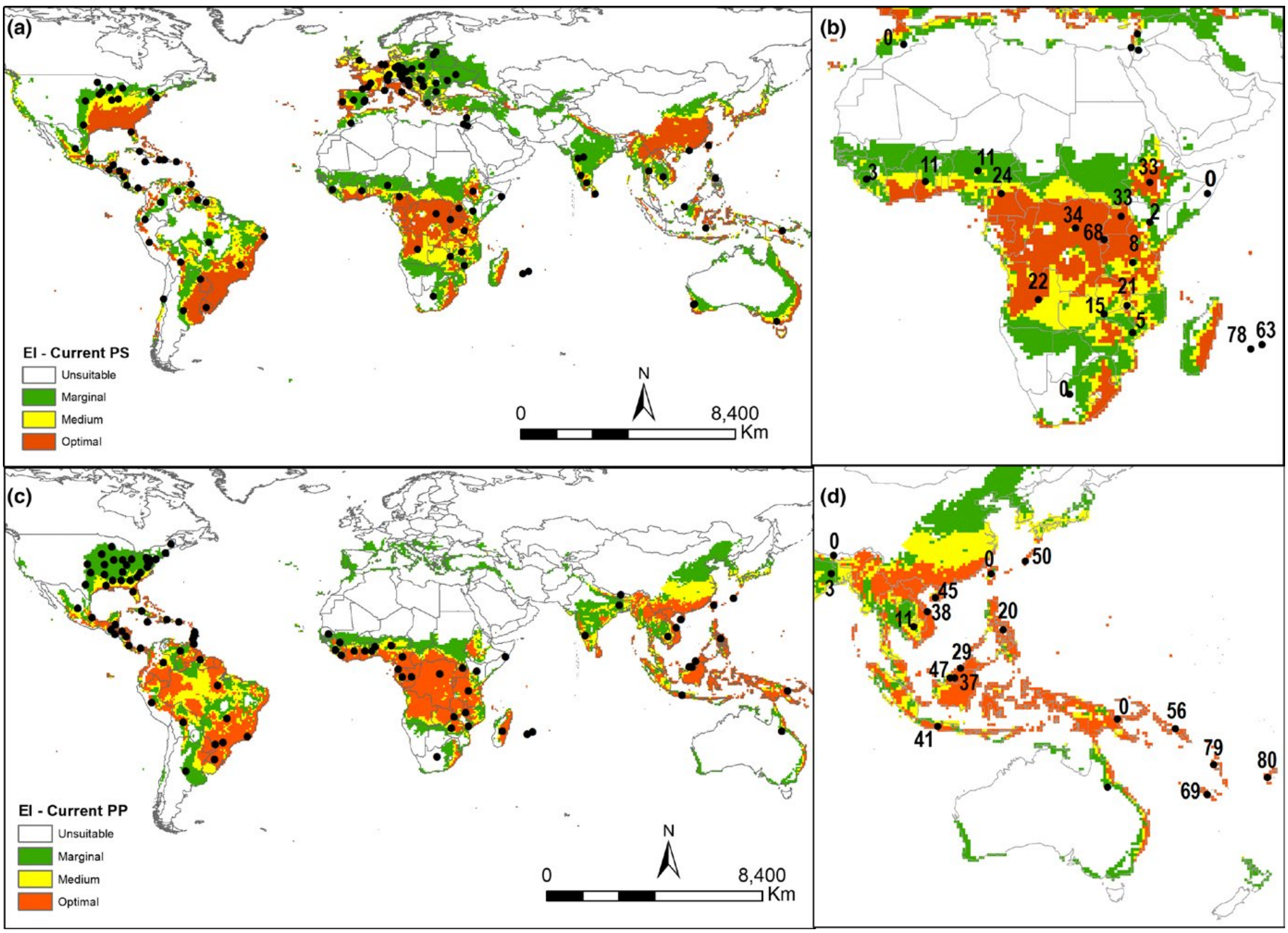

FIGURE 1 (a) Current global model of suitability distribution using CLIMEX with the parameter values of Table 1 for common rust, *Puccinia sorghi* (PS), the black dots show the geographical records of PS; (b) Validation area for the PS model with the EI values displayed. (c) Current global model of suitability distribution using CLIMEX with the parameter values of Table 1 for southern rust, *Puccinia polysora* (PP), the black dots show the geographical records of PP; (d) Validation area for the PP model with the EI values displayed

TABLE 1 Summary of CLIMEX parameter values for common rust (*Puccinia sorghi*) and southern rust (*Puccinia polysora*)

Index	Parameter	Acronym	Common rust	Southern rust
Temperature (GI)	Lower temperature limit (°C)	DV0	8	16
	Lower optimal temperature (°C)	DV1	16	23
	Upper optimal temperature (°C)	DV2	25	28
	Upper temperature limit (°C)	DV3	35	32
Moisture (GI)	Limiting low soil moisture	SM0	0.2	0.3
	Lower optimal soil moisture	SM1	0.7	0.9
	Upper optimal soil moisture	SM2	1.2	1.5
	Limiting high soil moisture	SM3	1.7	2.5
Stresses parameters	Cold stress temperature threshold (°C)	TTCS	8	0
	Cold stress temperature rate (per/week)	THCS	−0.00012	0
	Cold stress Degree-day threshold (°C days)	DTCS	0	8
	Cold stress Degree-day threshold rate (per/week)	DHCS	0	−0.0002
	Heat stress temperature threshold (°C)	TTHS	35	34
	Heat stress accumulation rate (per/week)	THHS	0.001	0.0002
	Dry stress threshold	SMDS	0.2	0.3
	Dry stress rate (per/week)	HDS	−0.005	−0.001
	Hot-wet temperature threshold (°C)	TTHW	30	0
	Hot-wet moisture threshold	MTHW	1	0
	Hot-wet stress rate (per/week)	PHW	0.005	0

GI, Growth parameters.
Values without units are dimensionless index of a 100 mm single bucket soil moisture profile.

(Roelfs & Bushnell, 1985); however, the minimum temperature reported for infection is 8°C (Headrick & Pataky, 1986). The THCS was set at 8°C with an accumulation rate of −0.00012 per/week. The cold stress degree-day threshold (DTCS) with its accumulation rate (DHCS) was used for southern rust. This method accumulates greater cold stress with higher values of DTCS, so more warmth will be necessary to prevent the cold stress. DTCS was used for southern rust because of its tropical nature. DTCS was set at 8°C with a rate of −0.0002 per/week. The use of these values precluded the persistence of southern corn rust in most of Europe, Canada, Russia, the north of China, and south of Chile and Argentina, where no records were found.

2.6 | Heat stress

There is no current or accurate information about how heat stress affects common or southern rusts. The heat stress temperature threshold (TTHS) and its accumulation rate (THHS) were set for heat stress. Experimental trials have determined the maximum temperature for *P. sorghi* from 30 to 35°C (Mahindapala, 1978a; Pivonia & Yang, 2006). The parameter values were set at 35°C for the threshold and 0.001 per/week for the accumulation rate. These values allow the disease to persist in India, Madagascar and New Zealand. The maximum cardinal temperature for preceding infection period of *P. polysora* was estimated at 42°C and for the infection period the value ranges from 27 to 32°C (Cammack, 1959; Godoy et al., 2003; Pivonia & Yang, 2006). In agreement with the previous experimental values, the TTHS was set at 34°C and its accumulation rate at 0.0002 per/week. These values prevent the spread of the diseases in the north west of Australia, northern of Africa and inner India.

2.7 | Dry stress

The dry stress threshold (SMDS) and the dry stress rate (HDS) were used to model the effect of the dry index on target corn rusts. The host dry stress is likely to affect the reproduction and survival of the rusts (Kriticos et al., 2013). For both fungal diseases, the dry stress was set to avoid the presence in dry locations such as inner Australia, the Sahara desert and Saudi Arabia where no presence of the main host has been registered. Experimental studies have demonstrated that under very dry conditions the viability of *P. sorghi* urediniospores was lost, in contrast with teliospores which can survive in dry conditions; however, the infection period is not tolerated in dry conditions (Ainsworth & Sussman, 1968; Cohen & Eyal, 1982; Mahindapala, 1978b). The SMDS was set at 0.2 and 0.3 with HDS of −0.05 per/week and −0.001 per/week, for common and southern rust, respectively.

2.8 | Wet stress

Wet stress was not used to limit the range of the corn rusts in this study because they are highly favourable to wet conditions and are not limited by this stress (Pivonia & Yang, 2006). Both rusts require short periods of leaf wetness to cause infection. Common rust has been found in Montecillos, Mexico with an annual rainfall of 645 mm (Gómez, Molina, García, del Carmen Mendoza, & de la Rosa, 2015). Additionally, southern rust has been found in Sete Lagoas, Minas Gerais in Brazil where annual rainfall exceeds 1,340 mm, and in Oyo State, Nigeria which has an annual rainfall of 1,022 mm (Akande & Lamidi, 2006; Pinto, 2004). It can be seen that the large amount of rainfall is not a stress factor.

2.9 | Hot-wet stress

Even when the physiological effect of this stress is unknown, a previous study showed that it could affect the host directly and indirectly in terms of the disease (Beddow, Hurley, Kriticos, & Pardey, 2013). Teliospores of *P. sorghi* are unable to survive long periods of high humidity (Mahindapala, 1978b), and due to this factor the hot-wet stress variable was used in common rust to limit its occurrence in the Amazon region and Indonesia, where very few reports of this disease have been recorded. This stress factor was not used for southern rust to allow for species occurrences in the Brazilian states of Para, Amazonas, Mato Grosso, Rondonia and Maranhao. The hot-wet stress threshold (TTHW) was set to 30°C with the hot-wet moisture threshold (MTHW) above 1, and a stress accumulation rate (PHW) of 0.005 per/week.

2.10 | Temperature index

The values for the temperature parameters were obtained from experimental studies. There are four parameters in CLIMEX to model the effect of temperature for the potential distribution of a species, being: the lower temperature threshold (DV0), the lower optimal temperature (DV1), the upper optimal temperature (DV2) and the upper temperature threshold (DV3). Below DV0 and above DV3, there is no growth, and the optimal growth is between DV1 and DV2. For common rust, experimental observations report that infection and development of symptoms do not occur below 8°C, and that the pathogen can survive in a latent period with temperatures below 4°C (Headrick & Pataky, 1986; Mahindapala, 1978b; Mederick & Sackston, 1972). The literature reviewed mentions optimal temperatures for common rust ranging from 15 to 28°C, and higher temperatures of 32°C for its survival (Casela, Renfro, & Krattiger, 1998; Cohen & Eyal, 1982; Mahindapala, 1978b; Mederick & Sackston, 1972; Pavgi & Dickson, 1961; Pivonia & Yang, 2006; Yeh, 1986). Based on the above information, the values for the temperature index for common rust were set as follows: DV0 = 8°C, DV1 = 16°C, DV2 = 25°C, DV3 = 35°C.

In the case of southern rust, hot humid conditions are required for survival, development and spread. The urediniospores of *P. polysora* have a narrow range of optimum temperatures, showing high temperature sensitivity. Optimal temperatures range from 23 to 28°C for germination (Pivonia & Yang, 2006; Roelfs & Bushnell, 1985; Yeh, 1986). Experimental observations showed that below 8°C, and above 40°C, *P. polysora* was not a viable infection (Hollier & King, 1985). In a previous study, a maximum temperature of 32°C was used to evaluate the infection of this pathogen (Pivonia & Yang, 2006). Other earlier experiments demonstrate that the germination is reduced when the temperature is below 13°C, and the pathogen did not grow at 7°C (Bushnell & Roelfs, 1984; Casela et al., 1998). Based on the above, the temperature index values for southern rust were set as follows: DV0 = 16°C, DV1 = 23°C, DV2 = 28°C, DV3 = 32°C.

2.11 | Moisture index

Moist conditions are required for the infection process of both diseases (Pivonia & Yang, 2006). The moisture index is related to available soil moisture, which can influence the relative humidity and leaf wetness levels necessary for growth, survival and spread of the infections. The limiting low soil moisture (SM0) was set higher than the wilting point most often used (Kriticos, Murphy et al., 2014), to reflect the preference for wet conditions. Highest possible values for the limiting high soil moisture were used (SM3) for both rusts. The moisture values were set and adjusted to allow for the persistence of common and southern rusts in the known locations. For common rust, the lower optimal soil moisture (SM1) was set at 0.7, the upper optimal soil moisture (SM2) at 1.2, SM0 at 0.2 and SM3 at 1.7. These values avoid the persistence of common rust in the western regions of Argentina, the USA, and inner regions in Australia. The values for southern rust were set to allow a marginally suitable persistence in southern Europe where the disease has not yet been reported (Cammack, 1959). The moisture parameters were established as SM0 = 0.3, SM1 = 0.9, SM2 = 1.5 and SM3 = 2.5. Due to the tropical and subtropical climate preference of this rust, the values were set higher than the values for common rust (Bushnell & Roelfs, 1984; Zhao et al., 2013).

2.12 | Combining GCM outputs of common and southern rust

The identification of common areas was established by overlaying the outputs of the two GCMs. Areas in common with marginal suitability for both rusts were categorized as low risk for the occurrence of both diseases. Areas in common with medium suitability for both species were identified as areas with moderate risk for the occurrence of both corn rusts. Finally, the combination of areas in common with optimal suitability for both diseases was identified as those areas to be under high risk. A similar process was followed for 2050 and for 2100 outputs. The resulting maps showed the common areas under different

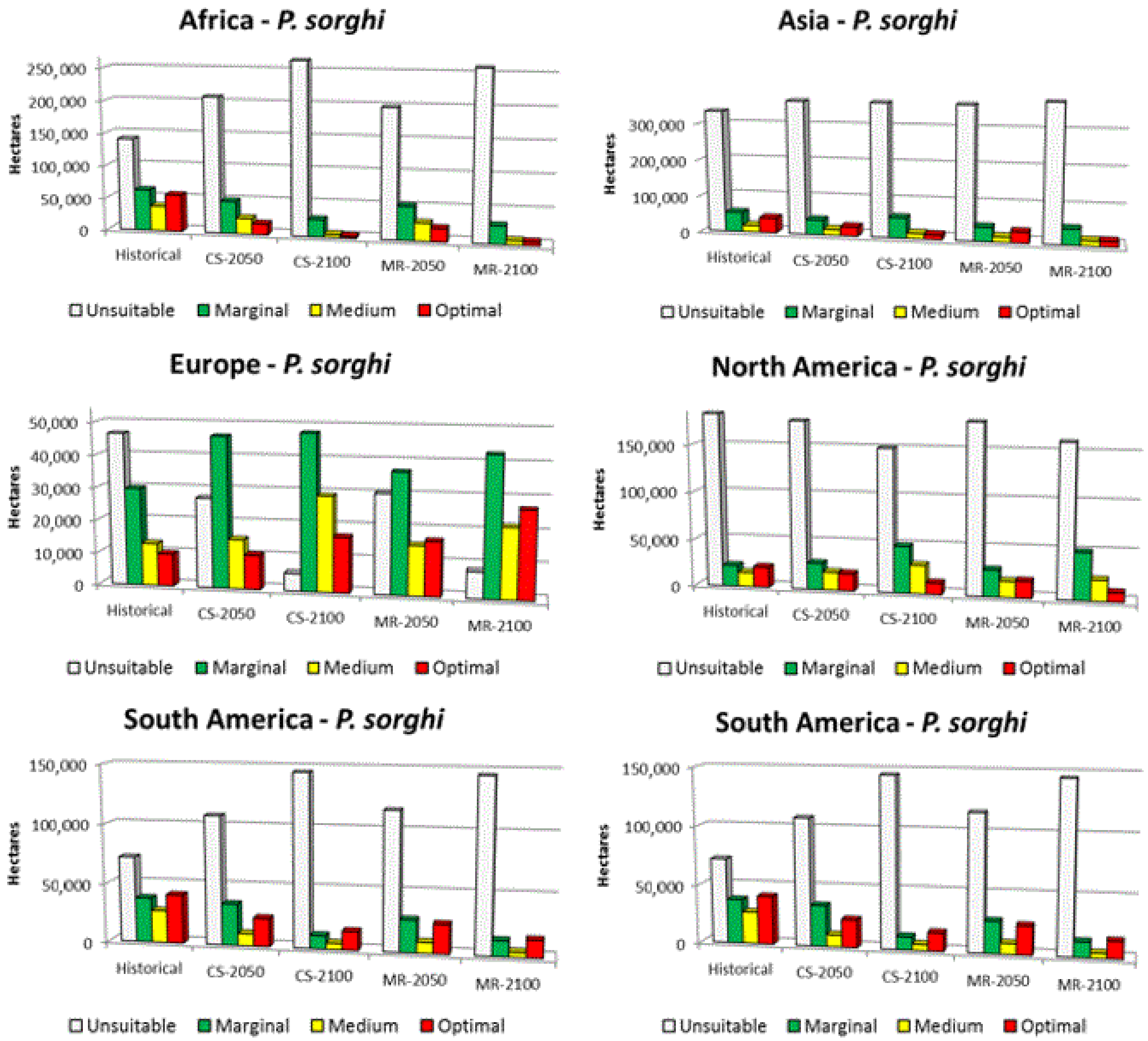

FIGURE 2 Projected areas of unsuitability and suitability for common rust (*P. sorghi*) by continent under historical and future projected climate

categories that are likely to be under risk for the simultaneous occurrence of both rusts.

A sensitivity analysis was carried out at a global level to measure the uncertainty of the parameter values in the models. The parameter values were adjusted above and below the fit value to calculate the range of change of the models.

3 | RESULTS

3.1 | Model validation, sensitivity analysis and current suitability

Two different areas were set aside for independent model validation. Africa was selected for the common rust; the model correctly predicts 16 occurrences out of a sample of 19 (84% accuracy). The Southeast Asian region was used to validate the southern rust model with 14 occurrences correctly predicted by the model out of a sample of 17 (82% accuracy) (Figure 1). The CLIMEX parameter values used to model the current distribution of common and southern rust matched the known distribution, confirming the reliability of the model (Table 1, Figure 1). Additionally, the results of the sensitivity analysis are summarized in Tables S3 and S4.

The model for current climate conditions for common rust shows the suitability for the occurrence of the fungus around the world. Southern China, the middle and eastern regions of Africa and southern Brazil showed optimal conditions for the occurrence of common rust. These conditions are similar in the Corn Belt of the USA, Central America and northern Argentina. Conditions with medium suitability are predicted for parts of the Corn Belt, different regions of Brazil, and regions of Angola, England, India and other countries. The marginal suitability is located mainly in India, Western Europe and some African countries. Canada, Russia, North Africa, the Middle East and most of Australia are projected to be unsuitable for the occurrence of common rust.

The current suitability projected for southern rust shows a more likely tropical distribution. The areas with optimal conditions for the occurrence are Central America, areas of Brazil, Argentina, Paraguay, most of the central and eastern Africa, and Sri Lanka. The regions with medium suitability are few, mainly in Brazil, Uruguay and China. The southern rust model showed marginal suitability for the Corn Belt of the USA, northeastern Argentina, southern Europe, minor regions of Latin-America, Africa, Asia and Oceania. Dry or cool places are projected to be unsuitable for southern rust. These data are reported in graph form in the supplementary material (Fig. S1 and S2).

3.2 | Future projections

CSIRO-Mk3·0 and MIROC-H had similar patterns for the projection for 2050 and for 2100. The areas are projected to be alike under both GCMs but with different levels of suitability. The models showed an overall increase in suitability in the Northern hemisphere, and decrease in suitability in the Southern hemisphere (Figures 2 and 3, Fig. S1 and S2). For common rust in Europe, the future suitability is projected to increase in area and intensity, with higher values of the EI in both periods. In Canada, the future suitability is projected to become marginal by 2100. The USA is likely to lose optimal suitability, but increase in the marginal category. Asia and Africa are projected to decrease in areas with suitability for the occurrence of common rust, along with

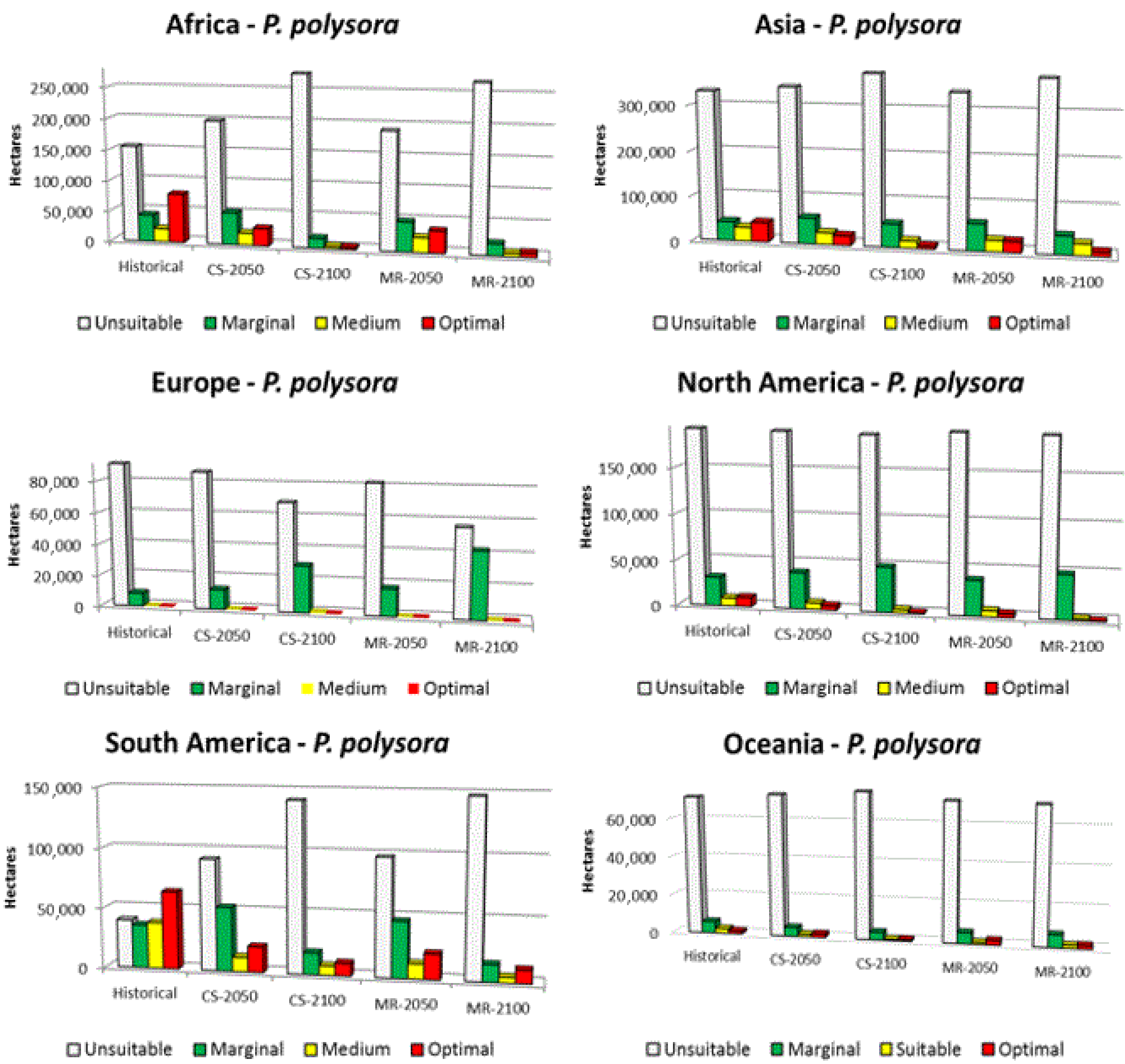

FIGURE 3 Projected areas of unsuitability and suitability for southern rust (*P. polysora*) by continent under historical and future projected climate

the intensity by 2050 and 2100 (Figure 2, Fig. S1). For southern rust, the projection for future suitability is a likely decrease in Latin-America, Africa and southeastern Asia. A small increase in marginal suitability is projected to occur in the USA and China. In Europe, the marginal suitability is likely to increase in area, especially by 2100. Uruguay is the only country that is likely to progress from medium to optimal suitability for this disease. Nearly, all the optimal suitability is lost in the projection under future climate conditions as observed for 2100 (Figure 3, Fig. S2).

In common rust, the hot-wet stress is highly likely to increase by 2100 in South-America and central Africa; the dry stress in the north of Mexico and the heat stress is projected to increase further in Latin-America, Africa and India; conversely, the cold stress is projected to decrease in the Northern hemisphere.

3.3 | Risk of occurrence in common areas for common and southern rust

CSIRO-Mk3·0 and MIROC-H agreement for common and southern rust for 2050 is shown in Figure 4a. America, Africa and Asia are projected to have more common areas with different levels of risk for the occurrence of both rusts. The largest area for high risk is projected to occur along the borders between Brazil, Uruguay, Paraguay and Argentina. Smaller areas of high risk are likely to occur in some African countries and China. Areas with medium risk are mainly in some US states. Also, small areas of medium risk are projected in Argentina, Brazil, Mexico, India, China and several countries in Africa with the exception of northern Africa. Low-risk areas are projected to occur in all the continents, with the smallest proportion in Oceania and the highest in the Americas (Corn Belt of the USA and Argentina).

Common areas projected to be extremely risky for the occurrence of corn rusts in 2100 are in Uruguay, southern Brazil, small parts of Argentina and China. The high-risk category is projected to decrease worldwide by 2100. The largest areas for medium risk are in northern Argentina, southern Paraguay and China. More than 50% of the medium suitability in 2050 is projected to become unsuitable for the occurrence of both rusts by 2100. The low-risk category is predicted to move up from the Corn Belt region of the USA to the Canadian border, with a similar trend projected for northern China. In Europe, climate will be more suitable for the occurrence of the corn rusts in the northern areas. Conversely, a decrease in the low-risk category is likely to occur in Mexico, Brazil, Argentina, India and Africa (Figure 4b).

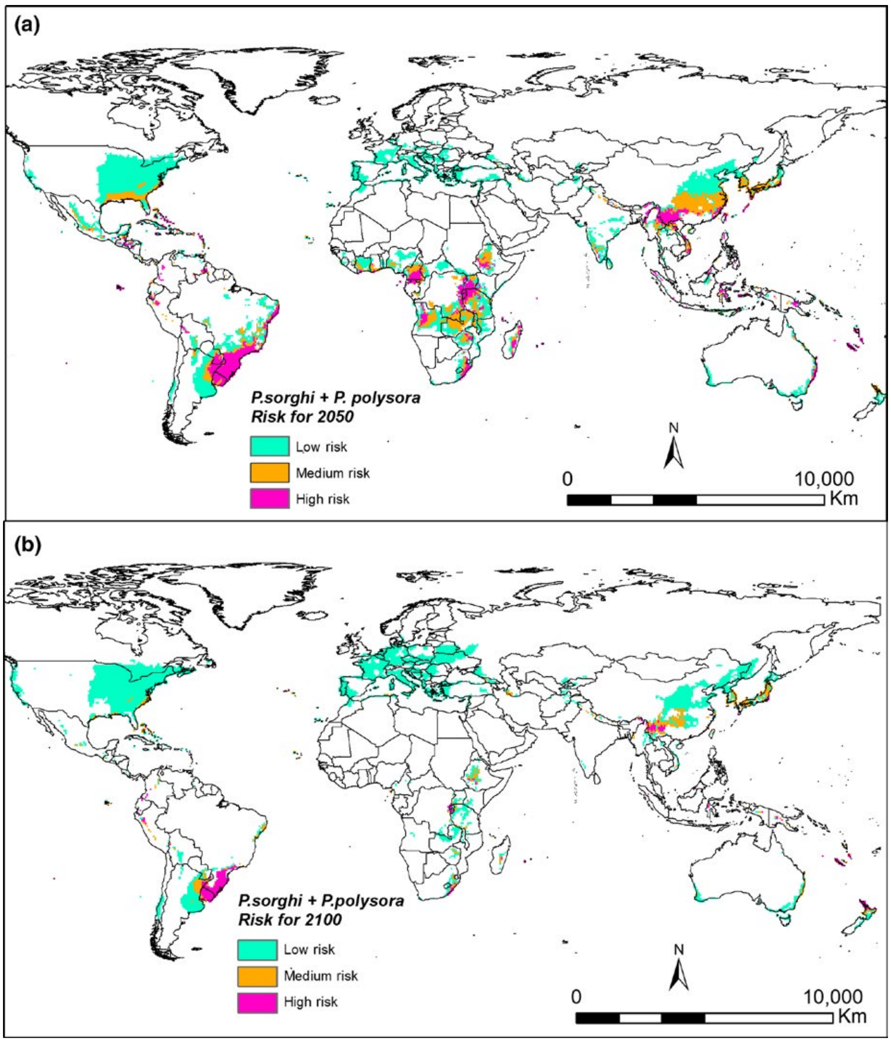

FIGURE 4 Common areas for the future model projections for simultaneous occurrence of common rust (*P. sorghi*) and southern rust (*P. polysora*) under A2 scenario and the agreement of CSIRO-Mk3·0 and MIROC-H, (a) by 2050; (b) for 2100

4 | DISCUSSION

The possibility to over-fit the model to get over-prediction could be done to get as many or all of the validation points into model predicted areas. However, if this was done, then the suitable areas in all the modelled areas would also increase, resulting in high suitability in regions where there are no records of the corn rusts and this would become apparent by looking at the maps (Figure 1). The independent database extracted from Africa and Southeast Asia allowed the accurate validation of the CLIMEX models, confirming the parameter selections (Tables S3 and S4). The consistency of the projected suitability and the seasonal phenology of the species acts as a cross validation in CLIMEX (Kriticos et al., 2015). Nevertheless, the current projection displays some areas without records, which may have occurred due the physical barriers, no suitable hosts in the area or lack of information about occurrences in that particular area (Kriticos et al., 2013). An example of this limitation is the case of China where no geographic records were available, but the existence and severity of southern rust have been reported (Zhao et al., 2013).

The current findings for the CLIMEX model projections of corn rusts show suitability in areas where corn is currently produced (Hartkamp et al., 2001). Therefore, these fungal diseases are highly likely to occur as the models display. Common and southern rust CLIMEX models show large areas with optimal suitability for Africa and Latin-America under current climate conditions; previous studies have shown that plant diseases are more frequent in these regions due to the tropical climate (Casela & Ferreira, 2002; Oerke, 2006). Moreover, southern rust is tropical and subtropical in distribution. These patterns are projected in the CLIMEX models for current climate conditions; the common rust suitability matches with the corn production areas and the southern rust is projected to have marginal to optimal conditions in the temperate areas of north-central Mexico and USA (Figure 1a).

The CLIMEX models for both GCMs outputs have similar trends; however, some differences are obvious. For example, the common rust model under CSIRO-Mk3·0 for 2100 projects a medium suitability for the Nordic countries, whereas the projection for the same year under MIROC-H projects mostly marginal suitability for these countries. The variations are explained by the different assumptions employed in the construction of the GCMs (IPCC 2007). Nevertheless, the aim of the present investigation is to provide a global perspective of the possible effects of climate change in the suitability of common and southern rust. The combination of both GCMs and the corn rusts increases the accuracy in the assessment of risk for future projections (Figure 4).

While the positive or negative effects of climate change in plant diseases are still uncertain, there will be effects for the different plant pathogens. Important groups of diseases and pests recorded originally in the tropics will spread globally. For example, bacterial and fungal diseases have been spreading to the Northern hemisphere since the mid-twentieth century (Bebber et al., 2013; Elderd & Reilly, 2014). The findings of this study agree with the tendency of fungi to move poleward, where cold stress is projected to reduce. Common rust is projected to move poleward on average by 10° and southern rust by 15° by 2100.

Further results for future climate project that current unsuitable regions (Figure 1a and 1c) are highly likely to become suitable for corn rusts, for example common rust in Canada, and southern rust in Europe (Figures 2 and 3, Fig. S1 and S2). The development and deployment of resistant host varieties could be useful to reduce the impact on corn yield losses; however, special care should be taken since there are different known races for common and southern rust (Le Roux & Dickson, 1957; Zhao et al., 2013). The new host varieties should confirm that resistance is effective for the races occurring in a determined region, and besides genes also respond differently depending on the environmental conditions (Hooker, 1967). Moreover, fungi are rapidly spread by air, seed and crop interchange, and in the past, once corn rusts were introduced into a new area these have spread rapidly (Akande & Lamidi, 2006; Dolezal et al., 2009; Godoy et al., 2003; Zhao et al., 2013). Special attention should be given to these areas where the increase in suitability is projected.

An interesting finding in this study is the decrease in suitable areas for these diseases in Latin-America by 2100, with the exception of Uruguay, northeastern Argentina and southern Brazil. This decrease is of great importance because it is well known that certain rust fungi cannot overwinter in the USA and may spread into the Corn Belt from Mexico (Roelfs & Bushnell, 1985). This finding may lead to the reduction in intensity of these rusts for the Corn Belt of the USA, one of the most important regions for corn production (Leff, Ramankutty, & Foley, 2004) (Fig. S1 and S2).

In future, milder winter in temperate areas will increase diseases; however, not all organisms will be affected in the same way by the increase in temperatures (Harvey et al., 1997). By 2100, common and southern rust are projected to decrease; the contraction of suitability is most noticeable for southern rust (Figures 2 and 3, Fig. S1 and S2). This is surprising because generally an increase in temperature is assumed to favour diseases; however, another effect of climate change is the reduction in precipitation (IPCC 2007). As these pathogens require wet conditions for germination, survival and reproduction, the pathogen may not be getting enough humidity. A further explanation for this reduction is that corn rusts, like most ectothermic organisms, do not have a linear growth, and the species have a short range of optimal temperature sensitivity (Pivonia & Yang, 2006); therefore, the growth rate is also dependent on temperature variability and not only on increases in mean temperature limiting the survival of the corn rust (Harvell et al., 2002). The heat stress increase in Africa, Latin-America and India also explains the loss of suitability for both rusts in these areas.

The overlaying of GCMs provides a higher level of reliability for the areas projected to be under low, medium and high risk by 2050 (Figure 4a.) and 2100 (Figure 4b) for common and southern rust. This combination presents a better perspective of the future impact of climate change because it is not limited to an individual GCM projection. Furthermore, these outputs show the common areas for the occurrence of two of the most important foliar corn diseases that affect corn yields worldwide to a large degree (Akande & Lamidi, 2006; Dey et al., 2012; Dolezal et al., 2009).

The Corn Belt of the USA and China are projected to have some level of risk for 2050, ranging from low to high. These regions are important because they harvest nearly 50% of the total global corn production (FAOSTAT, 2014). In the USA, crop production is highly technological and intensive (Leff et al., 2004). In contrast, in China mostly is cultivated by traditional methods (Bai et al., 2010; Gale, Jewison, & Hansen, 2014). Since common and southern rust can notably reduce corn yields and spread easily, the corn production in these regions can be exposed to high risk because of the large areas planted. In a similar situation to China, but with smaller planting areas, are Brazil, Mexico and some African regions. These are developing countries that by 2050 are projected to have areas from low to high levels of risk, and thus the hazard for these countries is more related to food security because corn is a staple crop and also contribute to household income (Bassu et al., 2014; Jones & Thornton, 2003). By 2100, fewer areas under high and medium risk are projected, and the risk is mainly projected to be low. However, precautionary measures should be taken. Another negative implication for regions with large planted areas of corn is that where corn is grown continuously, the rusts can spread from old plants, to young plants affecting susceptible stages and increasing yield losses.

Considering that the existence of a single rust disease in a corn plot is highly harmful for the crop, the occurrence of both diseases could cause the death of plants and increase corn yield losses. There are some additional factors that may prevent diseases. For instance, host varieties resistant to common rust have been used in USA with good effect, but this is not the case for southern rust (Pivonia & Yang, 2006). The southern rust epidemics around the world have been happening because there is no resistance in temperate corn although further efforts have been made to breed southern rust-resistant varieties in the current corn breeding programmes (Brewbaker et al., 2011; Zhao et al., 2013). However, to date there is no report of corn varieties resistant to both rusts, and in fact there is no evidence of any correlation between these rusts (Brewbaker et al., 2011). Additionally, the early planting of cold-tolerant corn germplasm may be an option to avoid the risk of these diseases because neither common rust nor southern rust are tolerant to cold stress (Revilla et al., 2003; Roelfs & Bushnell, 1985).

Moreover, diseases have been evolving constantly and consequently new and most virulent genotypes have emerged, such as *Puccinia graminis* and *Puccinia striiformis* (Bebber et al., 2013). There is currently little knowledge about how climate change will shape host–pathogen evolution and even with new resistant host varieties and the use of different management practices, the corn rusts may evolve and overcome host resistance (Altizer et al., 2013; Harvell et al., 2002).

It should be noted that the modelling was carried out using only climate data, and did not use other abiotic or biotic factors such as soil type, pathogens or biotic interactions between plants and enemies. These are modelling approaches but even with the actual knowledge of future climate change, uncertainty remains about future emission of greenhouse gases. Further investigation is required to understand to what extent plant diseases will affect corn production, the host–pathogen interaction, and consequently the food security and nutrition in developing countries, due to effects of climate change.

In summary, this study highlights the possible effects of climate change at a global level for common and southern rust, as well as the risk of occurrence of both diseases in common areas for 2050 and 2100. There is no doubt that effects of climate change on plant disease will threaten global food security. In some regions, there is a high likelihood of an increase in suitability (Northern hemisphere) and in others a decrease (Southern hemisphere). Most disease risk is predicted to increase due to climate change; however, some diseases may decline in frequency and intensity. The occurrence of two or more pathogens could lead to the death or extinction of the host, and further plant diseases may also affect associated fauna. The effects of climate change in pathogens could be positive, creating new opportunities for their distribution, or negative by limiting their suitability. Given that the changes in plant diseases may have important economic and ecological consequences, the present outputs may provide information for formulation of policies, for long-term agricultural planning.

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