



An examination of how climate change could affect the future spread of *Fusarium* spp. around the world, using correlative models to model the changes



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ABSTRACT

Climate change is predicted to have a significant impact on the geographic distribution of various flora, fauna, and insect species by expanding, contracting, or shifting their suitable climate environment. The plant pathogenic fungus *Fusarium* is known for causing crop diseases like blight, root and stem rots, and wilts, making it the most significant mycotoxigenic genus in weeds and food across various climatic zones worldwide. In this study, we hypothesize that crop diseases caused by *Fusarium* spp. will increase across all four corners of the world by 2050 and 2070 in response to future climate conditions. A series of correlative species distribution models (SDMs), including a generalized linear model (GLM), maximum entropy (MaxEnt), generalized boosting model (GBM), and surface range envelope, were employed to project and compare how the niche of *Fusarium* spp. will change from the present time to 2050 and 2070 under two Climate Change Representative Concentration Pathways (RCPs) of 8.5 and 4.5 (scenarios of high and low greenhouse gas emissions, respectively). Our approach (the ensemble predictions of 4 SDMs) minimizes the uncertainty (differences) of the projection results from each one of the models. The findings of this study have global implications because *Fusarium* spp. are associated with host species that are present on major continents such as Asia, Europe, Australia, and North and South America. The information gathered could be beneficial to farmers and planners when creating strategies to prevent the proliferation of *Fusarium* spp. as well as calculating the expenses associated with using pesticides to minimize contamination and increase yields.

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1. Introduction

Fusarium spp., a genus of fibrous ascomycete fungi, is known for producing a variety of toxins that have major implications for agricultural production. These fungi can cause a range of diseases in both agricultural and natural settings, such as rots, blights, cankers, and wilts in forest crops, ornamental plants, and horticulture plants (Ma et al., 2013). For the classification of 70 species of *Fusarium* spp., Leslie and Summerell (2006) combined the anatomical, biological, and phylogenetic species ideas. One of the most significant genera of phytopathogenic fungi, *Fusarium* spp., impacts various crops in diverse climatic zones (Summerell, 2019). Several forms of the genus can be found in plants and soil all over the globe

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as pathogens, endophytic fungi, and saprobes (Sireli et al., 2022). Among the most significant families of phytopathogenic fungi identified in horticulture and agriculture, *Fusarium* spp. causes various diseases on various crops (Aslam et al., 2017; El-Baky and Amara, 2021; Wang et al., 2022). For example, two species of *Fusarium* spp. i.e. *Fusarium graminearum* and *Fusarium oxysporum*, produce head blight of *Triticum aestivum*. In contemporary phytopathology, many wilt and stem rot diseases are among the top 10 pathogens for economic and scientific investigation. Further, it has been documented that 83 of 108 species of plants have one or even more *Fusarium* spp. infections affecting their productivity (D'mello et al., 1999; Doohan et al., 2003; Magan, 2007). Therefore, it goes beyond merely plant issues. Trichothecenes and fumonisins, two mycotoxins produced by *Fusarium* spp., are particularly harmful to the animals as well as the ability to negatively impact human health (Furian et al., 2022). A plethora of species also infect people with diseases, particularly immunocompromised individuals, which frequently have catastrophic results (Kortei et al., 2022). A serious disease that affects smaller crops like barley, wheat, maize and oat is *Fusarium* spp. Head blight caused by various *Fusarium* species (Parry et al., 1995; Skelsey and Newton, 2015). *Fusarium oxysporum* f. spp causes many diseases in garlic, tomato, banana and palm (Shabani et al., 2014). *Fusarium verticillioides* and *Fusarium graminearum* are primarily responsible for maize cob rots and both species release mycotoxins that infect the cereals. Some types of *Fusarium* spp. induce collar rot in leguminous seedlings like peas and beans (Burgess, 1981; Reid et al., 2002; Seethapathy et al., 2017). Vascular wilt disease is mainly caused by *Fusarium oxysporum*, root and collar rots are caused by *Fusarium solani*. Melons and potato tubers rot is the result of certain *F. oxysporum* strains (Bahadur, 2021; LeBlanc et al., 2017; Srinivas et al., 2019). *Fusarium* spp. as phytopathogen causes diseases including head blight, crown rot and scab on cereal grains as well as vascular wilts, cankers, root rots, and other conditions like sugarcane's pokkah-boeng and rice's bakanae disease (Aoki et al., 2014; Bahadur, 2021; Booth, 1971; Okungbowa and Shittu, 2012; Shabeer et al., 2021).

Climate influences the growth and spread of *Fusarium* spp. infections (Murillo-Williams and Munkvold, 2008; Nazari et al., 2014; Vaughan et al., 2016). *F. graminearum* seems to be the predominate *Fusarium* species harmful to barley, wheat and maize in hotter portions of the world, such as the USA (Ghimire et al., 2020; Halpern et al., 2018). Similar to this, extremely heavy rainstorms may expose crops to saprophytic fusaria, which can cause soft rots (Jiménez-Díaz et al., 1989). According to Backhouse and Burgess (Bentley et al., 2006), the occurrence of *F. graminearum* was restricted to hot temperate to tropics with moderate to the substantial rainy season during the summer, whereas the presence of *F. pseudograminearum* was unrestricted by weather factors and it was common across the majority of Australian crop-producing regions (Gagiu et al., 2022). Asexual conidia and sexual ascospore generation and distribution of *Fusarium* spp. are significantly influenced by humidity, wind, light intensity, and temperature (Champeil et al., 2004; Crane and Bergstrom, 2014).

Climate change is having an influence on agricultural crop yields as well as the frequency and severity of crop epidemic diseases all over the globe (Beddington, 2010; Chakraborty, 2005; Stern and Stern, 2007). The production of agricultural crops is anticipated to decline over time as a result of climate change, particularly if there are no initiatives to reduce worldwide emissions of CO₂ (Skelsey and Newton, 2015; Wu et al., 2011). Extreme weather patterns brought on by climatic changes may predispose crops to damage and increase their vulnerability (Pörtner et al., 2022). For example, drought-like circumstances may increase the prevalence of bacterial and fungal wilt (MacIntyre et al., 2022). By raising CO₂ in the atmosphere, diseases caused by *Fusarium pseudograminearum* may thrive in more favorable environments. Further, the prevalence of the organisms responsible for the various infections in barley, wheat and maize ear rot is frequently associated with various climatic variables like temperature, CO₂ concentration and rainfall in various geographic regions (Paterson and Lima, 2017; Rossi et al., 2009). It is also documented that depending on whether the fungi reproduce sexually or asexually, different environmental variables impact the formation and spread of the inoculum (Dix, 2012; Ojeda-López et al., 2018). The spread of *Fusarium* spp. infection takes place during specific climatic conditions like the drop in temperature and rising humidity (Pfordt et al., 2020; Rossi et al., 2001). Different *Fusarium* species infect optimally at different temperatures. The optimum infection temperature for the *F. avenaceum* and *F. graminearum* is 28.0 to 29.0 °C while for *F. culmorum* is 26.5 °C (Bernhoft et al., 2012; Rossi et al., 2001). Climate requirements vary across *Fusarium* species, for example, *F. avenaceum* (−3–31 °C), *F. oxysporum* (5–37 °C), *F. poae* (2.5–33 °C), *F. proliferatum* (2.5–35 °C), *F. culmorum* (0–31 °C) and *F. graminearum* at 5–30 °C (Brennan et al., 2003; Doohan et al., 2003; Manstretta and Rossi, 2016; Rossi et al., 2001). Table 1 shows the list of food borne *Fusarium* species with their host.

Previous research (Shabani et al., 2014) has investigated the impacts of climate change on the niche of *F. oxysporum* using a semi-mechanistic model, but that study was limited to Europe, the Middle East, and parts of North Africa. Records of *F. graminearum* have been found on all continents except Antarctica, and its estimated distribution covers the majority of the world's major rainfed wheat-growing regions, with the exception of the warmest parts of south Asia, according to BIOCLIM analysis by Backhouse (2014). *F. graminearum* is most prevalent in northern China, Japan, and Korea, while *F. asiaticum* predominates in southern regions (Lee et al., 2012; Suga et al., 2008). This distribution pattern is thought to be influenced by temperature, as thermal impacts and the interplay between moisture and temperature on infection vary among *Fusarium* species and impact the dispersion of different species (Parikka et al., 2012). Previous studies have used CLIMEX, MaxEnt (Alkhalifah et al., 2023) to investigate the distribution of *Fusarium* spp, but our study uses four species distribution models as an ensemble of 4 SDM results would minimize the uncertainty (differences) of the projection results from each one of the models.

Species distribution models (SDMs) have been widely used to estimate species distribution alterations under changing climates and create ecological suitability mapping under current circumstances (Fyllas et al., 2022; Yebeyen et al., 2022).

Table 1*Fusarium* species with their corresponding hosts

<i>Fusarium</i> species	Hosts	References
<i>Fusarium avenaceum</i>	Apples, cereals, pears peaches, potatoes, peas, peanuts, tomatoes, asparagus	Bahadur (2021), Logrieco et al. (2003), Nikitin et al. (2023)
<i>Fusarium oxysporum</i>	Apple, beans, cereals, nuts, peas, bananas, potatoes, onions, citrus fruits, processed juices, cheese and spices	Bahadur (2021), Logrieco et al. (2003), Nikitin et al. (2023), Pitt and Hocking (2022)
<i>Fusarium sambucinum</i>	Potatoes, cereals	Heltoft et al. (2016), Peters et al. (2008)
<i>Fusarium semitectum</i>	Bananas, potatoes, citrus, nuts, melons, spices, tomatoes	Dhall (2016), Perumal et al. (2022), Pitt and Hocking (2022)
<i>Fusarium sporotrichioides</i>	Pome fruits and cereals	Astapchuk et al. (2020), Manshor et al. (2012)
<i>Fusarium equiseti</i>	Fruits and cereals contaminated with soil, nuts, vegetables, spices, processed juices	Agriopoulou et al. (2020), Ünüsan (2019), Zinedine and Mañes (2009)
<i>Fusarium tricinctum</i>	Cereals	Kulik et al. (2011), Zinedine and Mañes (2009)
<i>Fusarium solani</i>	Spices, vegetables and fruits	Bhaliya and Jadeja (2014), Ownagh et al. (2010)
<i>Fusarium poae</i>	Cereals, soybeans, cereals, rice, sugar cane	Bahadur (2021), Creppy (2002), Modrzewska et al. (2022), Munkvold et al. (2021)
<i>Fusarium cerealis</i>	Potatoes, cereals	Cooper et al. (1988), Palacios et al. (2021), Stefańczyk et al. (2016)
<i>Fusarium venenatum</i>	Potatoes, cereals	King et al. (2018), Thomas et al. (2017)
<i>Fusarium subglutinans</i>	Pineapple, spices bananas, sorghum and corn	Bahadur (2021), Ploetz (2006), Seepe et al. (2021)
<i>Fusarium verticillioides</i>	Rice, bananas, sugarcane, corn, asparagus, cheese, garlic, spices	Bahadur (2021), Logrieco et al. (2003), Nikitin et al. (2023)
<i>Fusarium proliferatum</i>	Fruits, rice, corn, figs	Li et al. (2012), Proctor et al. (2010)
<i>Fusarium culmorum</i>	Potatoes, cereals, sugar beet, apple	Boyd-Wilson et al. (2000), Parry et al. (1995), Pasquali et al. (2013)
<i>Fusarium graminearum</i>	Grasses and cereals	Fulcher et al. (2019), Kelly and Ward (2018), Matelioniene et al. (2022)

SDMs assist in identifying the major environmental elements that influence distribution and abundance by modeling a species' habitat (Yebeyen et al., 2022). SDMs mimic habitat appropriateness by combining current presence data with a variety of environmental parameters, such as edaphic or climatic factors, but combined species distribution modeling has also been suggested (Clark et al., 2014; Elith and Leathwick, 2009).

When modeling species distributions, it can be challenging to determine which model to use, and different models can produce variable results (Shabani et al., 2016). Furthermore, certain models may work well for one species but not for others. When projecting multiple species into novel environments or independent areas, it may be less reliable to choose a single "best" model, and instead, an ensemble modeling approach may be more appropriate. It is also essential to understand the accuracy of the model's predictions, and while tools like TSS and fractional predicted areas are suitable for measuring accuracy between model results, AUC has been found to be less reliable. Thus, in this study, we used four SDMs and an ensemble approach to reduce the uncertainty and differences in the projection results from each model. Well-known techniques for projecting the past/present/future distribution of species include CLIMEX, GARP, HABITAT, and MaxEnt, and in many studies scientists employ one technique only (Alkhalifah et al., 2023). (Alkhalifah et al., 2023) used MaxEnt and *bio1* (annual mean temperature), *bio2* (mean diurnal range (mean of monthly max temp–min temp)), *bio7* (temperature annual range), *bio12* (annual precipitation), and *bio14* (precipitation of driest month) environmental variables in predicting *F. oxysporum* habitat suitability while (Shabani et al., 2014) used CLIMEX as a semi mechanistic model.

Hence, our study aims to employ a set of correlative SDMs (generalized linear model, MaxEnt, generalized boosting model, and surface range envelope) to project and compare how the niche of *Fusarium* spp. will change from the present time to 2050 and 2070 under two RCPs of 8.5 and 4.5 (scenarios of high and low greenhouse gas emissions, respectively) on a global scale. We also intentionally focused on 6 randomly selected countries (Australia, Tunisia, Canada, France, China, and Qatar) to highlight potential niche changes over time and space, but our results are also illustrated on a global scale. Our study hypothesizes a constant increase in the climate suitability of *Fusarium* spp. in all four corners of the world between the present time, 2050 and 2070 in response to future climate conditions.

2. Materials and methods

2.1. Occurrence records

The occurrence records for *Fusarium* spp. were downloaded from the Global Biodiversity Information Facility (GBIF, www.gbif.org). Additionally, reports of fieldwork and findings from other scientific research studies that have been published were incorporated. There are total 72,502 locations where *Fusarium* spp. is reported. The GBIF data showed the presence of *Fusarium* spp. in Australia, Asia, Europe, South America, and North American countries whereas less information was found in the Middle East and Russian areas.

2.2. Climate variables

Climatic variables extracted from the WorldClim dataset (worldclim.org) were used, with a granularity of 2.5 minutes (4.5 km²), as dispersion indicators for three-time frames (the present, 2050, and 2070). The variance inflation factor was calculated prior to modeling using the *usdm* package (Naimi, 2015) and a correlation threshold of 0.7 was used to identify multicollinearity amongst response variables (Ahmadi et al., 2017). Six factors were ultimately chosen as potential distribution predictors: ((i) *bio1* (annual mean temperature in °C); ((ii) *bio4* (temperature seasonality = standard deviation × 100); ((iii) *bio5* (maximum temperature of the warmest month in °C); ((iv) *bio12* (annual precipitation in mm); ((v) *bio14* (precipitation of the driest month in mm); and ((vi) *bio19* (precipitation of the coldest quarter). The spread of the species was projected and predicted over a broad global scale using these climatic factors to account for yearly, seasonally, and comparative environmental traits that could influence the species' growth circumstances.

2.3. Species distribution modeling

To forecast favorable climatic conditions for *Fusarium* spp., the *biomod2* package array framework was used for species dispersion modeling in the R environment (Thuiller et al., 2009). To predict suitable climatic conditions for *Fusarium* spp. A unanimous model, or “ensemble” model, is produced by simultaneously processing numerous modeling methodologies (Araújo and New, 2007; Thuiller et al., 2009). To create a unified forecast of the climatic suitability for *Fusarium* spp., four strategies were adopted for the ensemble projections: MaxEnt, generalized linear model, generalized boosting model, and surface range envelope (also referred as “BIOCLIM”). Instead of attempting to anticipate the species' actual range, our goal was to create projections of relative climatic appropriateness. 75% of the occurrence data (training data) were used for model calibration, while the residual 25% was kept aside for model performance analysis. In light of the known ability of these indicators to respond to prevalence in species distributions, we employed the area under the curve AUC (receiver operating characteristic) and the true-skill statistic (TSS) to assess the performance of the models (Araújo and New, 2007; Swets, 1988). The *biomod* framework was used to quantify the individual efforts of each variable in the models of species distribution, and response curves obtained from each model were used to assess how the species distributions responded to ranges of explanatory factors. Finally, the ensemble forecasts were computed using the weighted average of each model's evaluation statistic (Thuiller et al., 2009).

To create a “core” region with appropriate climate conditions for each of the forecasted periods, the locations most suited for *Fusarium* spp. were determined before designing the finalized distribution models. Then, using a quantile classification approach, these anticipated core areas were compared with the present appropriate time to determine the extent of region change throughout different periods (2050 and 2070).

2.4. Thresholds

A fitness threshold was driven using the relative suitability map, (Guillera-Arroita et al., 2014) below which we determined the species to be “missing”. In the SDMs, this threshold technique is frequently used to convert continuous the probability of presence to presence/absence data (Nenzén and Araújo, 2011; Pearson et al., 2002). Ecology frequently uses the 10th- and 5th-percentile training presence levels (Pearson et al., 2002). Other approaches include defining a particular specificity or sensitivity threshold, trying to maximize specificity plus sensitivity (Cantor et al., 1999), optimizing kappa (that contains all these specificity and sensitivity), increasing the percentage of correctly identified points, and increasing the agreement between predicted and observed results dispersion (Guisan et al., 1998). In order to widen the study, the 5th percentile threshold was also examined, along with the maximum specificity plus sensitivity, for the purpose to evaluate the performance. Initially, the 10th percentile of the appropriateness score was computed at present points.

2.5. Global circulation models

The 19 future models of global circulation are available in the WorldClim database. The Community Climate System Model (CCSM4; www.cesm.ucar.edu/models/ccsm4.0) and the Model for Interdisciplinary Research on Climate-Earth Systems Model (MIROC-ESM) (Watanabe et al., 2011) were the two that we chose since they were consistently accessible over the periods we took into consideration (2050 and 2070) In comparison to utilizing only one, using several global circulation models improves projection dependability while retaining accuracy (Schepen and Wang, 2013).

2.6. Background data

Common statistical approaches require that the whole region of interest has been randomly or methodically sampled since it is a fundamental presumption that data collected are independent (i.e., randomly assigned samples with independent distributions). In reality, places that are easier to assess and/or well-studied are favored by existing data on the species' locations (Kramer-Schadt et al., 2013). This phenomenon is considerably more likely to occur with data from worldwide datasets (such as those from the Global Biodiversity Information Facility GBIF or the Atlas of Living Australia) that come from many sources and have variable field sample levels and sizes (Wisiz et al., 2008). Spatial autocorrelation across sites can however lead to skewed parameter estimations and over-representation of particular regions, even if some approaches (like MaxEnt) can handle geographically biased data more effectively than others (F. Dormann et al., 2007). Background weighting and spatial filtering (Elith et al., 2010) are two techniques used to lessen the impact of any biases in the presence spots of the simulated species (Renner and Warton, 2013). All duplicate spots were eliminated within a 5-km buffer radius for spatial filtering. To avoid skewing model predictions, background weighting was used instead of randomly selecting pseudo-absences. In this case, we gave the model environmental data that was skewed in space as occurrence data. Then 10,000 background points were used to calculate the parametric layer of a species' occurrence points, which were used to determine the probability of the dense surface.

2.7. Model performance

Although calculations based on existing data have limits for ecological realism in the simulated dispersion, the region under (receiver operating characteristic) curve is a solid indicator of discriminating capacity (Jiménez-Valverde, 2014; Lobo et al., 2008). Since the true-skill statistic (TSS) is independent of prevalence, we also utilized it to evaluate model performance. For our models, specificity and sensitivity are independent of one another as well as of prevalence, which is the percentage of all cells that detected the existence of a species. The true-skill statistic has been shown (Allouche et al., 2006) to be a simple way to evaluate the accuracy of SDMs used for absence–presence mapping.

3. Results

3.1. Model performance and spatial outputs

In general, all the SDMs performed well for the species as evidenced by the true-skill statistic and the area under the curve. (AUC > 0.93 and TSS > 0.79). Figs. 1 and 2 show the mean ensemble model suitability map for the three time periods (the present, 2050, and 2070). The top panel in Fig. 1 demonstrated the occurrence record and coordinates of *Fusarium* spp. across the globe. Australia showed the highest dispersion and occurrence. *Fusarium* spp. has been reported in Europe, Africa, some parts of Asia, and North and South America. Similarly, in randomly selected countries such as Tunisia, Canada, France, and China, the presence of *Fusarium* spp. has also been reported. However, in the Middle East, specifically in Qatar, no records of this species have been reported.

The middle panel showed the range of suitability (Low and high suitability) of *Fusarium* spp under the current state of the climate. It explains that the areas with high suitability for growth and development are red in color, on the other hand, the areas where low suitability is present are blue in color. Data for *Fusarium* spp. in Middle Eastern countries, particularly Qatar, is not well documented, but it is present in these regions. The second panel shows similar results to the top panel. By comparing the two panels (present time and occurrence record), we can see the similarity in the regions affected by *Fusarium* spp. The bottom panel in Fig. 1 is a binary map of *Fusarium* spp. distribution, with suitable areas represented in red and unsuitable areas represented in white. The bottom panel clearly shows the regions where *Fusarium* spp. are present and where it has fewer chances of survival. The visual results in the bottom panel support the findings of the top two panels, with the map of Australia being completely red, and some parts of Tunisia, Canada and France being red, but Qatar being completely white, indicating the absence of *Fusarium* spp in this region.

3.2. Changes vs present-time distribution

The application of GLM, MaxEnt, GBM, and surface range envelope allows us to track changes between the present and future. The maps in Fig. 2 signify the importance of the modeling approach to study the potential changes in different regions of the world. According to the suitability classifications depicted on these maps, right column in Fig. 2 displays the current and projected distribution of this species. The left column in Fig. 2 showed a continuous map for two emission scenarios like RCP 4.5 and RCP 8.5 in 2050 and 2070. The overall area of *Fusarium* spp. that is suitable for it is decreased in some major parts of the world as compared to the current occurrence record in Fig. 1. The SDM models produced the future distribution of *Fusarium* spp. species under the hypothetical predicted climatic values for 2050 (RCP 4.5 and RCP 8.5) that were compared with present the distribution of the existing species. The findings in (Fig. 2) demonstrated that, in comparison to the existing distribution (Fig. 1), there would be a decrease in moderately and highly appropriate regions according to estimated future forecasts from the bioclimatic MaxEnt model of 2050 (RCPs 4.5 and 8.5). It is also demonstrated in Fig. 2 that the western and southern parts of Australia which are now suitable will become less suitable

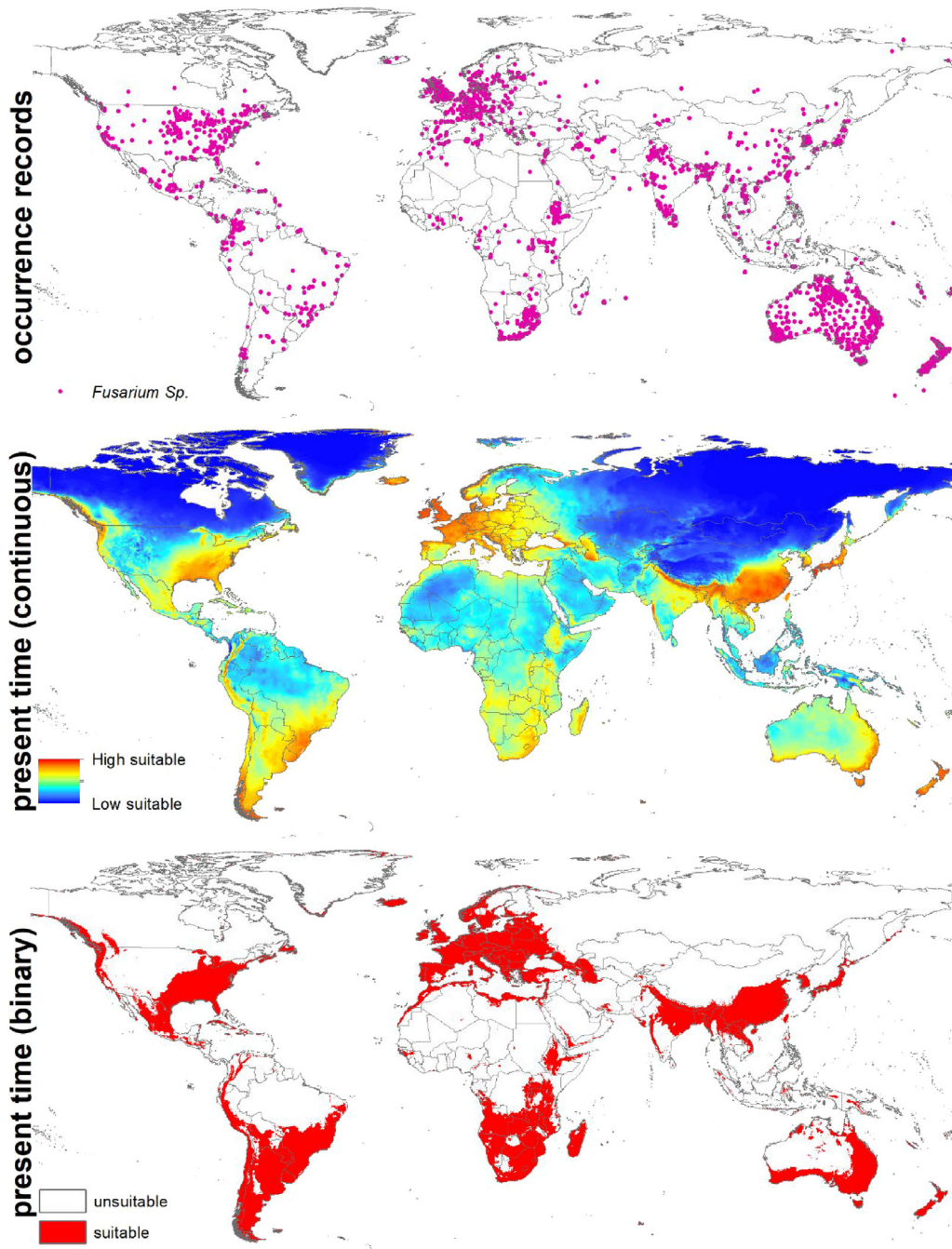


Fig. 1. Top panel indicates the current distribution of *Fusarium* spp., central panel is the ensemble predictions based on a generalized linear model, MaxEnt, generalized boosting model, and surface range envelope model outputs (climate suitability) at present time and the warm color indicates the highest suitability and cool color indicates the lowest; bottom panel is a binary map of output (suitable & unsuitable) for the present time. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for *Fusarium* spp. in 2050 under both scenarios (RCPs 4.5 and 8.5). The same is the case with central American countries like Brazil and some parts of Bolivia which are showing a shift towards the south. The right panel in Fig. 2 showed the areas where suitability will increase, decrease, or remain the same. The randomly selected countries like Australia, Tunisia, Canada, France, and China showed significant results (RCP 4.5) in 2050. But for Qatar, there is no change in visual results in the right column (White).

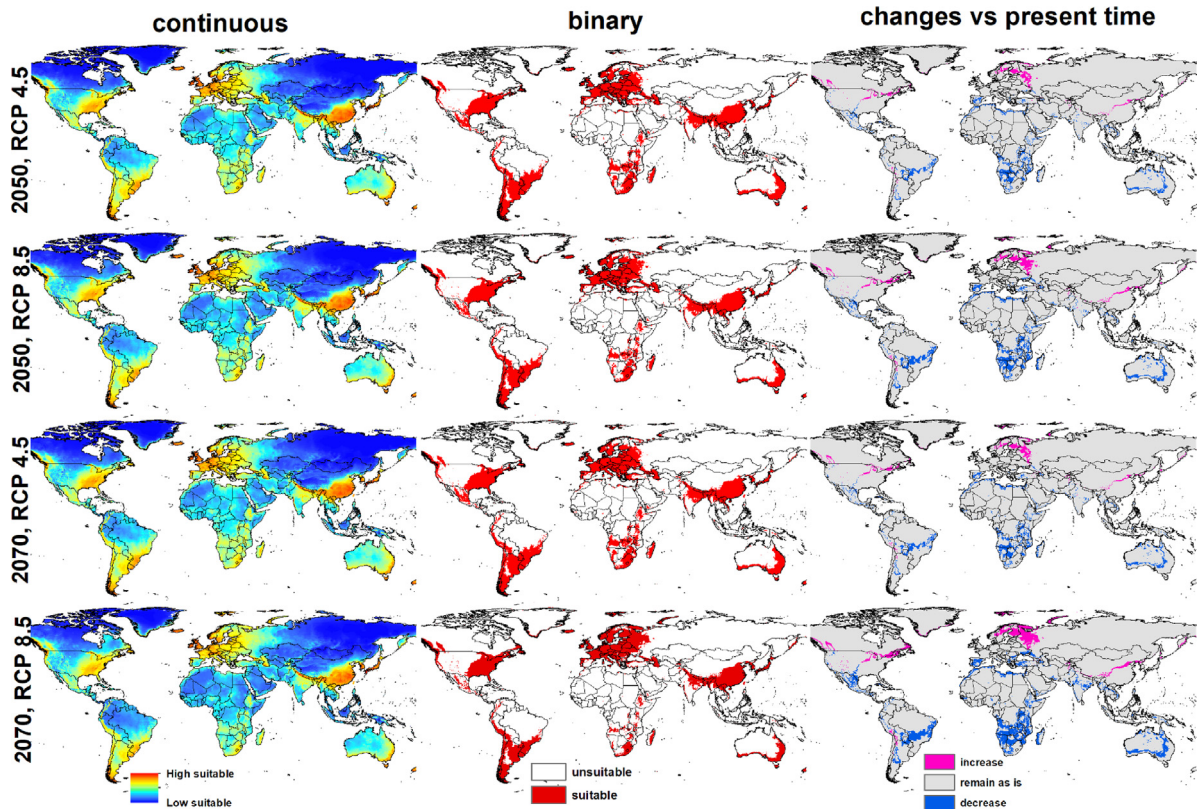


Fig. 2. Continues and binary maps of climate suitability of *Fusarium* spp. by 2050 and 2070 under RCP 4.5 and 8.5; the right panel indicates climate suitability alteration of the corresponding year and RCP vs present time. Results are the ensemble predictions: generalized linear model, MaxEnt, generalized boosting model, and surface range envelope (also known as 'BIOCLIM'). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Similarly, the MaxEnt model of 2070 (RCPs 4.5 and 8.5) in Fig. 2 lower two panels demonstrated that central and western Africa will become significantly less suitable for the *Fusarium* spp. The northern and coastal lines of Africa are showing the same result. Under the two different scenarios, the possible geographic dispersion of *Fusarium* spp. in the 2070s was different from those in the present. Both the low and high suitable areas decrease, indicating less tendency toward development. Among them, the central part of Australia, Africa, and North and South America mostly showed a rise in the lowly appropriate regions whereas the outer territory of Russia also showed a rise. It means in the next three to five decades the geographical and climatic conditions will become unsuitable in these areas for the growth and spread of *Fusarium* spp. The right column in Fig. 2 demonstrates the regions across the world where climate suitability will increase, decrease, or remain the same. The visual map demonstrated that some regions of the world will become more suitable for *Fusarium* spp. (Pink color) some will not change (Gray color) and in some area suitability is decreased (Blue color).

3.3. Percentage gain and loss in the distribution of *fusarium* spp. in selected countries

By comparing the global distribution of *Fusarium* spp. with its projected geographic distribution in 2050 and 2070 under the RCP 4.5 and RCP 8.5 climate scenarios in Fig. 2, the alterations were discovered. Data from two separate periods were compared to identify any changes. The existing and projected geographic spread of *Fusarium* spp. was categorized to achieve variation. Fig. 3 depicts the percentage gain in the climate suitability of *Fusarium* spp. in some countries under both scenarios i.e., RCP 4.5 and 8.5 in 2050 and 2070 respectively. The Fig. 3 showed a greater than 5% gain in climate suitability for *Fusarium* spp. in both climate scenarios. Russia demonstrated the highest gain (325%) in climate suitability for *Fusarium* spp. in 2070 under RCP 8.5. The same pattern was observed for 2050 RCP 8.5 for Russia. Although, there is no big increase in the climate suitability in Russian for RCP 4.5 for 2050 and 2070 respectively. The climate suitability in 2070 RCP 8.5 is increased for Uzbekistan, Tajikistan, Afghanistan, Kyrgyzstan, North Korea, Canada, Sweden, and Greenland (refer to Table 1 in the supplementary information file). There is a slight increase in climate suitability for the United States, Japan, Bhutan, Bolivia, Peru and Turkmenistan. Overall, the highest increase was observed for RCP 8.5 and 2070. The increase was not highly significant for RCP 4.5 in 2050 and 2070. The findings in table 1 show that Svalbard and Jan Mayen, Finland, Uzbekistan, Russia, Kazakhstan, Tajikistan, Afghanistan, North Korea, Canada, Sweden, Greenland,

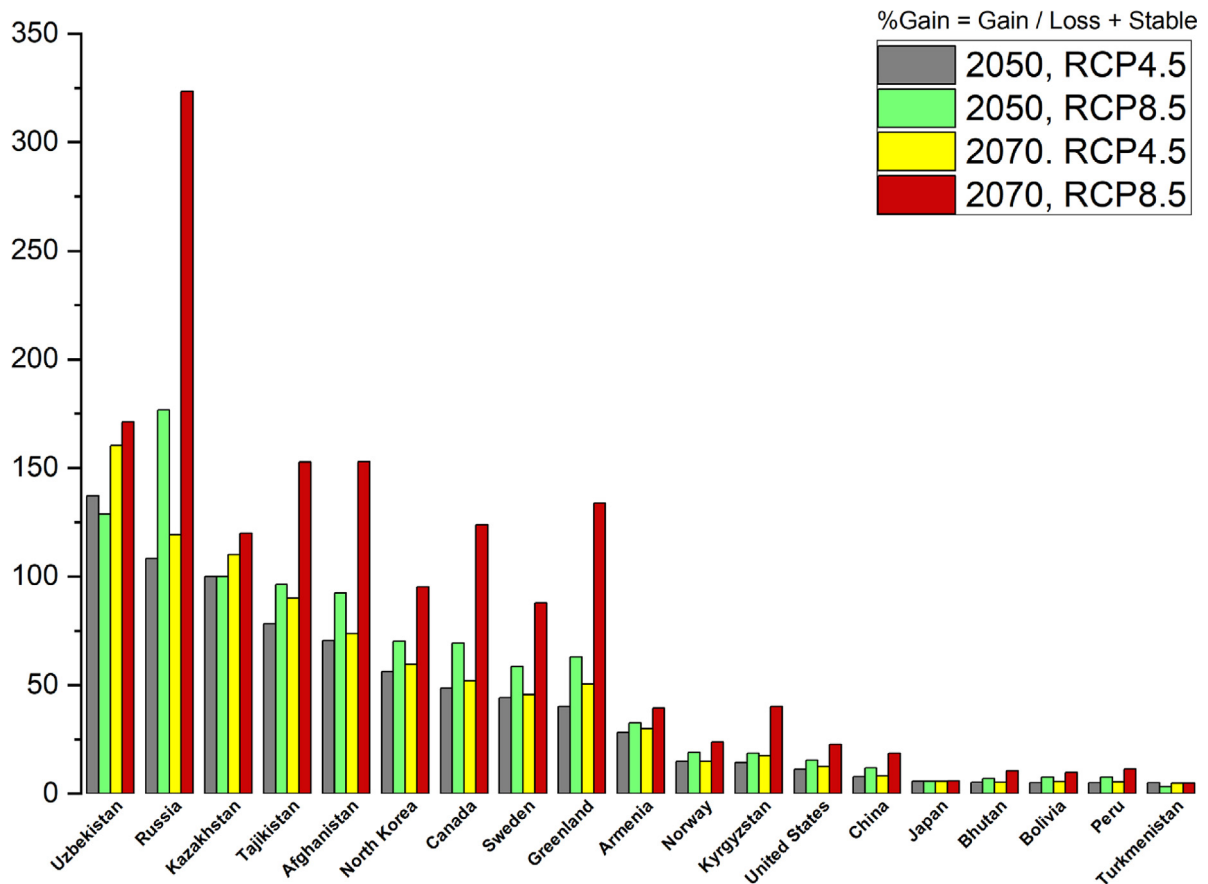


Fig. 3. Continues with a total Gain in climate suitability greater than 5% for *Fusarium* spp. by 2050 and 2070 under RCP 4.5 and 8.5; Comparisons are based on the projected corresponding year and RCP vs present time.

Armenia, Norway, Kyrgyzstan, United States, China, Japan, and Bhutan showed significant gain climate suitability at RCP 8.5 in 2050 and 2070. In these countries, the increase was greater than 5% and the highest increase was observed for Svalbard and Jan Mayen (2387.5%) in 2050 RCP 4.5 while the gain was (6925%) for 2070 RCP 8.5 (Table 1 supplementary file). The percentage gain in suitability for the randomly selected countries like in 2050 RCP 4.5 was (Australia 0%, Tunisia 0%, Canada 48.6%, France 0%, China 7.8% and Qatar 0%). The percentage gain in suitability in 2070 RCP 8.5 was (Australia 0%, Tunisia 0%, Canada 123.9%, France 0%, China 18.6%, and Qatar 0%). The percentage gain of other countries is available in the supplementary file.

Fig. 4 depicts the percentage loss in the climate suitability of *Fusarium* spp. in some countries under both scenarios i.e RCP 4.5 and 8.5 in 2050 and 2070 respectively. Togo, Senegal, Turkmenistan, Malaysia, and Tunisia along with many other countries demonstrated a significant loss in climate suitability for *Fusarium* spp in 2070 and 2050 under RCP 8.5. The same pattern was observed for RCP 4.5 for these countries. Although, there is no big loss in the climate suitability in Laos, Peru, Myanmar, and Vietnam for RCP 4.5 in 2050 and 2070 respectively. The climate suitability in 2070 RCP 8.5 is decreasing for Bulgaria, Afghanistan, Lebanon, and many other countries mentioned in Fig. 4. Overall, the loss in climate suitability was observed for RCP 8.5 and 2070. The loss was not highly significant for RCP 4.5 in 2050 and 2070. Table 1 data demonstrate 100% loss in climate suitability observed for countries such as the Central African Republic, Côte d'Ivoire, Dominica, Mayotte, Saint Kitts and Nevis, Solomon Islands, Togo, and the United Arab Emirates. Other countries like Senegal, Guyana, Congo, Gabon, Belize, Cambodia, and Turkmenistan showed >90% loss in climate suitability. Other countries including Mauritania, Malaysia, Fiji, Panama, Saudi Arabia, Cuba, Cameroon, Western Sahara, Chad, Libya, Botswana, Guinea-Bissau, Kazakhstan, Djibouti, Equatorial Guinea, Tunisia, Iraq, Oman, Egypt, Nigeria, Comoros, Jordan, Somalia, Algeria, and Guadeloupe showed more than 50% decrease in environmental suitability. The percentage loss of other countries is available in the supplementary file.

3.4. Percentage gain and loss in the distribution of *fusarium* spp in Qatar and selected countries

The randomly selected regions of the world such as Australia, Tunisia, Canada, France, and China are experiencing changes in mean temperature, rainfall patterns, and other environmental factors that are impacting the growth and

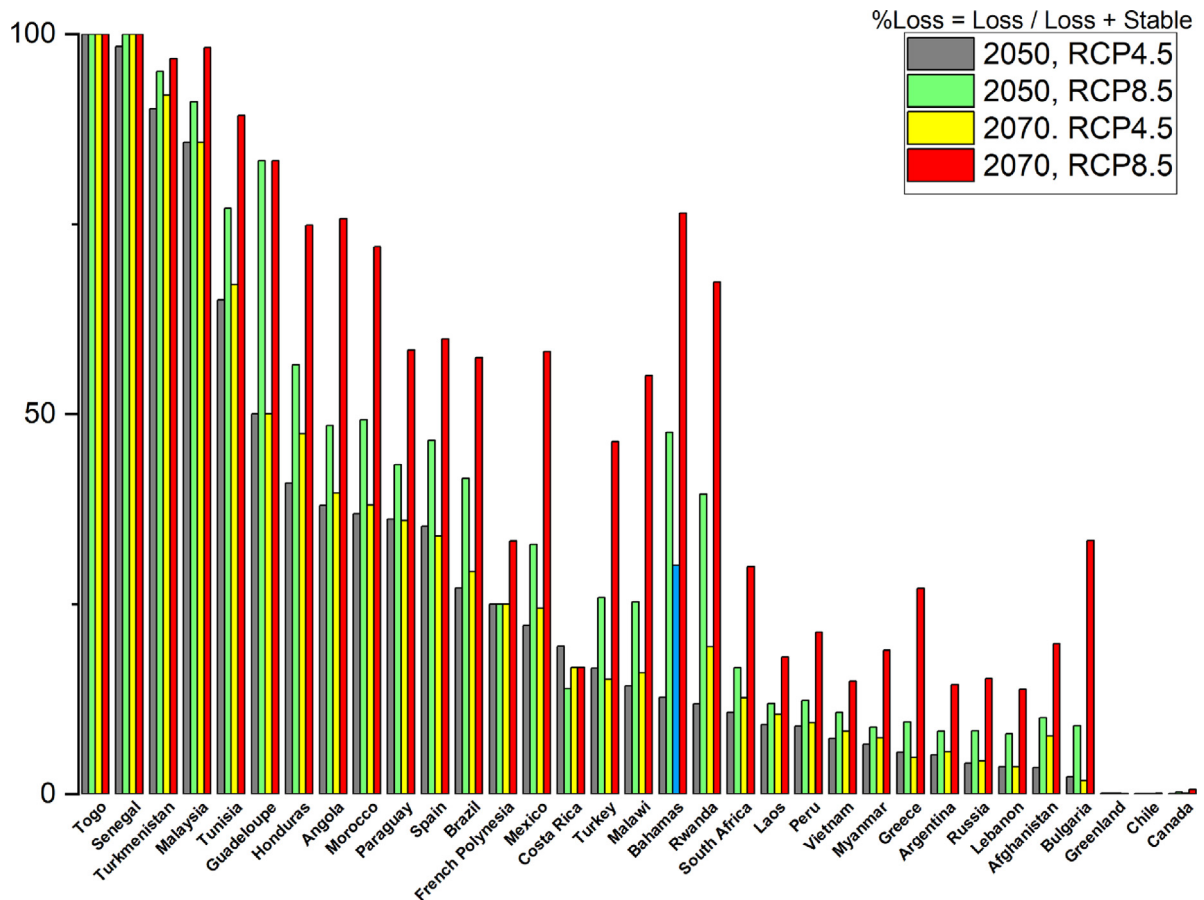


Fig. 4. Randomly selected continues with loss in climate suitability for *Fusarium* spp by 2050 and 2070 under RCP 4.5 and 8.5; Comparisons were based on the projected corresponding year and RCP vs present time.

development of *Fusarium* spp in these regions. According to the results of our modeling exercise, these countries displayed variations in the dispersal of *Fusarium* spp. Similarly, Qatar is an arid country with high summer temperatures and high pressure of anthropogenic activities in the Arabian Peninsula, and its extreme weather conditions make the ecosystem unique compared to other regions where *Fusarium* spp is prevalent. Fig. 2 shows that Qatar is not suitable for the growth and spread of *Fusarium* spp. It is also clear that in both climate scenarios, RCP 4.5 and RCP 8.5, in 2050 and 2070, Qatar remains unaltered. In Table 1 (supplementary), Qatar did not show any gain or loss of climate suitability (loss and gain are 0) in the models. This may be due to the lack of reported and submitted data on *Fusarium* spp distribution in databases like GBIF. The percentage gain in suitability for the randomly selected countries like in 2050 RCP 4.5 was (Australia 0%, Tunisia 0%, Canada 48.6%, France 0%, China 7.8%, and Qatar 0%). The percentage gain in suitability in 2070 RCP 8.5 was (Australia 0%, Tunisia 0%, Canada 123.9%, France 0%, China 18.6%, and Qatar 0%). The percentage loss in suitability for the randomly selected countries like in 2050 RCP 4.5 was (Australia 29.3%, Tunisia 65%, Canada 0.1%, France 0%, China 0% and Qatar 0%). The percentage loss in suitability in 2070 RCP 8.5 was (Australia 49.5%, Tunisia 89.3%, Canada 123.9%, France 0.6%, China 0%, and Qatar 0%). The percentage gain and loss data for other countries are available in the supplementary file.

4. Discussion

It is well-established that changes in global climate such as soil, temperature, and rainfall can affect species' geographic ranges (Gray et al., 2009). In response to global climate change, scientists have developed algorithms that can predict future fungal distribution regions based on various environmental factors and provide valuable data for understanding current plant distribution (Yackulic et al., 2013; Thibaud et al., 2014). The key variables influencing the growth of *Fusarium* species that cause significant infections of maize and some other small grain products are temperature and precipitation. However, various environmental conditions, such as extra fungal infections, drought tolerance, or host factors, also impact how these climatic elements are felt (Bottalico, 1998; Miller, 2001). Similar research in this field suggests that ecological

loss and dispersal, as well as declines in biodiversity, would all be significantly impacted by climate change (Kelly et al., 2016; Murgia et al., 2019).

It was possible to recognize variations between specific geographic areas based on climatic parameters like the annual range of temperature, seasonal fluctuations, yearly range or average temperature of the rainiest quarter, and annual rainfall or rainfall patterns of the rainiest quarter. The temperature fluctuations were not as significant as the variation in rainfall amounts during a short time frame. This variability is a significant factor affecting the proportions of the species *F. verticillioides*, *F. temperatum*, *F. subglutinans*, and *F. proliferatum*. According to several accounts, the prevalence of *F. graminearum* fluctuates greatly across years and locales in many different geographical areas. The mapping of validated data proved the worldwide distribution of *F. graminearum* (O'Donnell et al., 2000). These all species have been implicated in the head blight of wheat. Although *Fusarium graminearum* has been found on every continent, the other species in the complex have so far been found in locations that are more constrained (Backhouse, 2014). Records covering most of the major wheat-growing regions were gathered from all continents, except for Antarctica. In addition to the regions covered by site records, *Fusarium graminearum* has also been found in Russia, Japan, England, and Turkey (Gagkaeva and Yli-Mattila, 2004; Suga et al., 2008; Yörük and Albayrak, 2012). According to BIOCLIM, each of these locations should have favorable climatic conditions for *F. graminearum*. Other *Fusarium* species have been identified in limited surveys in Tunisia, Mexico and Ethiopia. In northern Tunisia *F. graminearum* species complex was not detected, with *F. culmorum* being the most abundant species (Fakhfakh et al., 2011). An alternate analysis that was more closely related to factors that impact the *F. graminearum* was supplied by the climatic envelope, which was based on average weather conditions at anthesis like annual mean temperature and rainfall (Wright et al., 2010). It is, nevertheless, considered to be a dominating species in North America, and Central and Northern Europe, such as in Poland (Chelkowski, 2014; Ward et al., 2008), the Czech Republic (Czembor et al., 2015), Austria or Slovenia (Lew et al., 1991). whereas *F. verticillioides* is more common in southern European nations like Spain and Italy (Beyer et al., 2014; Boutigny et al., 2014; Munoz et al., 1990). Recently, climatic fluctuation has influenced the spread of *F. verticillioides* in regions throughout Central Europe and the population instability of *Fusarium* species (Dorn et al., 2009; Scauflaire et al., 2012). Similarly, the rising levels of *Fusarium* spp infections in Date palms in southern Tunisia showed considerable signs of abrupt decline and fruit rot in the years 2017–2018 (Rabaoui et al., 2021). Our results indicate that in 2070 (RCP 8.5) there will be a loss of 89.3% in the suitability of *Fusarium* spp in Tunisia. There are many diseases caused by *Fusarium* spp reported in cereals crops in France (Orlando et al., 2019). According to Marín et al. (1996) and Torres et al. (2003), *F. verticillioides* grows and germinates best at a temperature of around 25 °C. According to Reid et al. (1999), *F. verticillioides* germinate and grow across a greater variety of temperatures and water activities than *F. graminearum*. For *F. verticillioides* to grow, a temperature of 4 °C is necessary, whereas 10 °C is needed for *F. graminearum*. Our findings showed that the global *Fusarium* spp distribution is changing, and temperature is one of the factors which affect distribution across the globe. Due to global warming, the climate is changing and like other species *Fusarium* spp also showed a response to changing climate. It was reported that the population of *Fusarium* spp is changing in China, North America, Luxemburg, Norway, South Korea, New Zealand and Europe (Valverde-Bogantes et al., 2020). In Europe and Asia, the distribution of *Fusarium* species is highly influenced by climatic suitability, resulting in their occurrence in different countries (Yli-Mattila, 2010). A study by Gale et al. (2011) reported fluctuation in the distribution of *Fusarium* spp. in Europe. *F. asiaticum*, which has not yet spread beyond its center of origin in Asia, is absent in most regions. (Gale et al., 2011). Qu et al. (2008) hypothesized that the relative abundance of *F. asiaticum* and *F. graminearum* is correlated with mean annual temperature. In Australia, the distribution of *Fusarium* spp. was found in warm temperate to subtropical regions with moderate to high summer rainfall and mean temperatures over 18.7 °C and rainfall over 195 mm, as per the BIOCLIM model analysis (Backhouse and Burgess, 2002). However, the changing climate is impacting the distribution of *Fusarium* spp. by altering the annual mean temperature and rainfall pattern (Backhouse, 2014; Backhouse and Burgess, 2002). Our study's findings are consistent with those of another study, indicating that *Fusarium* spp. dispersion is changing in Europe, Australia, New Zealand, and the USA. The suitability of *Fusarium* spp. is decreasing in tropical areas with extremely high temperatures. The minimum temperature in Qatar has significantly increased due to the warming trend resulting from changes in air circulation across the Sudan, Mediterranean Sea, and Indian Ocean (Almazroui et al., 2014; AlSarmi and Washington, 2014). This temperature rise is making the area unsuitable for the growth of *Fusarium* spp., resulting in a financial impact on the agriculture sector in the Middle East due to the pathogen's reduced occurrence.

Qatar aims to become self-sufficient in the agricultural sector, so it has begun to grow its agricultural resources. To do this, Qatar imports grains and feeds grown in various geoclimatic zones, and these grains and feeds may carry spores of *Fusarium* spp. with them. In one study, *Fusarium* spp. was reported in marketed feed in Qatar (Hassan et al., 2019) but not in the natural habitats of Qatar, which aligns with the model findings that it is not present in Qatar (Fig. 2 and Table 1). The findings of this study can help planners and managers consider the potential impacts of *Fusarium* spp. on crops, fruits, and vegetables in Qatar. *Fusarium* spp. is damaging the yield of crops like wheat, banana, onion and many other cereals crops which are used as food (Labanska et al., 2022; Modrzewska et al., 2022). If food production continues to decrease, it can potentially lead to a major food security problem as the world's population is increasing at a rapid rate and the demand for food is higher (Petronaitis et al., 2021). If food production decreases due to *Fusarium* spp, it may be necessary to consider eradication efforts or shifting farming to areas that will become less suitable for its growth. Even though there is ample evidence that both abiotic factors and biotic interactions greatly impact species' distribution at various spatial scales, most SDMs do not take these impacts into account (Zimmermann et al., 2010).

5. Conclusion

This study is a crucial first step in understanding how climate change could impact the global distribution of *Fusarium* spp, which are known to cause infections in major crops such as cotton, tomatoes, and bananas. The findings of this study can have significant economic implications for the affected crops. The study revealed that *Fusarium* spp have a global distribution, except for Antarctica, and the distribution of these species is projected to change significantly in Asia, Europe, Australia, and North and South American nations. Further, our study employed SDMs to create prediction maps for the current and future distribution of *Fusarium* spp under various anticipated climate scenarios. This approach offers an improvement over earlier modeling techniques that focused on predicting how global warming might affect the distribution of these fungi using models such as CLIMEX, MaxEnt, and BIOCLIM. The distribution maps generated by this study could be useful for designing and implementing cost-effective agricultural methods. Our study also highlighted several regions that are currently unsuitable for *Fusarium* spp infection in cereal crops and bananas but are projected to become more conducive to the growth of these fungi over the next three to five decades. This is likely to result in a decline in the yields of these crops, creating a significant challenge to food security. As such, the findings of this study should encourage managers, city planners, and farmers to think about the long-term consequences of their management practices. We note that severe cold and hot conditions could constrain the growth of *Fusarium* spp, and additional research is needed to better understand the variables influencing population trends and regional demographic differences of these fungi, particularly in regions that have yet to be explored. Overall, this study provides valuable insights into the potential impact of climate change on *Fusarium* spp and highlights the need for ongoing research and action to address this pressing issue.

CRedit authorship contribution statement

Muhammad Riaz Ejaz: Conceived and designed the experiments, Performed the experiments, Analyzed the data, Contributed reagents/materials/analysis tools, Wrote the paper. **Samir Jaoua:** Conceived and designed the experiments, Performed the experiments, Analyzed the data, Contributed reagents/materials/analysis tools, Wrote the paper. **Mohsen Ahmadi:** Conceived and designed the experiments, Performed the experiments, Analyzed the data, Contributed reagents/materials/analysis tools, Wrote the paper. **Farzin Shabani:** Conceived and designed the experiments, Performed the experiments, Analyzed the data, Contributed reagents/materials/analysis tools, Wrote the paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.eti.2023.103177>.

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