

Article

Biogeography of Black Mold *Aspergillus niger*: Global Situation and Future Perspective under Several Climate Change Scenarios Using MaxEnt Modeling

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Abstract: Climate change impacts represent one of the most important ecological and medical issues during this century. Several fungal species will change their distribution through space and time as a response to climate changes. This will rearrange many fungal diseases throughout the world. One of the most important and very common fungi is the black mold *Aspergillus niger*. The COVID-19 pandemic reforms the way in which mycologists think about this fungus as an emerging healthy issue. Through this work, about one thousand records of *Aspergillus niger* were used to model its current and future global distribution using 19 bioclimatic variables under several climate change scenarios. Maximum entropy implemented in Maxent was chosen as the modeling tool, especially with its accuracy and reliability over the other modeling techniques. The annual mean temperature (bio 1) forms the most contributed climatological parameter to black mold distribution. The produced current distribution model came compatible with the real distribution of the species with a cosmopolitan range. The rise of temperature due to global warming will form a limitation to *Aspergillus niger* through several parts of its range. The generated maps of the future status of this fungus under two different RCPs for 2050 and 2070, indicate several parts that become free from black mold due to temperature limitations. The present results need more intensive future evaluation using data science and GIS, especially on a local scale including more ecological parameters other than climatological data.



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1. Introduction

Aspergillus niger is a well-known fungus belonging to the genus *Aspergillus* with a worldwide distribution [1]. Due to the fact it can colonize a variety of substrates, it is widely spread and has been found in several habitats [2]. *A. niger* is a saprophyte that can be found on compost piles, stored grain, dead leaves, and other decomposing vegetation [1,3]. The spores are found in a wide range of organic materials and soil [3]. Many of the asexual spores produced by conidiophores are resistant to environmental stressors, allowing the organism to survive during times of inactivity [3,4]. On the other hand, *Aspergillus* infections result in considerable morbidity and mortality [5]. *A. fumigatus* is the most common, followed by *A. flavus* and *A. terreus*. *A. niger* is a mold that has only been recognized as a cause of pneumonia on a few occasions [5].

Invasive pulmonary aspergillosis (IPA) is a common consequence in patients with severe respiratory syndromes and is linked to a high mortality rate [6]. It is caused by the *Aspergillus* genus [7]. Many causes contribute to the development of IPA, the most common

of which are chronic corticosteroid treatment and lung epithelial injury [6]. IPA has been identified as a super-infection in patients suffering from severe respiratory illnesses such as influenza and MERS-CoV [8]. Many severe respiratory syndrome cases caused by COVID-19 (SARS-CoV-2) have been diagnosed with IPA since December 2019 [9]. The clinical impact of this infection is characterized by a dysregulated immune response and extensive lung damage, which leads to the onset of secondary infections early [8,9].

The infection with the black mold is hastened by the spores [3]. When *A. niger* spores are deposited on a solid or liquid surface and the conditions of moisture and food are appropriate, climatic parameters such as humidity and temperature are extremely important in dispersing spores in the air for short and long distances. Once the spores are deposited on a solid or liquid surface and the conditions of moisture and food are appropriate, they germinate [3]. A few studies on airborne fungi found that when air temperatures were between 15 and 25 °C and relative humidity was between 60 and 70%, fungi spore concentration increased [10].

Climate change has traditionally been viewed as a social justice issue [11]. By the 1980s, when climate change was becoming recognized as a policy issue and large-scale research was being conducted, it was evident where the problem began (the rich's carbon dioxide emissions) and where the consequences would be felt the most (the poor countries in the tropics) [11]. This core idea has not changed after ten or fifteen years of continuous investigation, but it has deepened our understanding of causes and mechanisms [12]. As a result of increasing CO₂ levels, the Intergovernmental Panel on Climate Change (IPCC) predicts a 1.8–4 °C increase in global temperature by the end of the twenty-first century [13,14]. This sort of change will potentially disrupt ecosystems worldwide, affecting biological processes and reducing the biodiversity of living organisms, including fungi.

Predicting biodiversity's response to climate change has become a significant subject of study [15,16]. To anticipate the current and future state of a species, environmental niche modelling compares the species' records to a panel of environmental characteristics, including climatological data [17]. A number of studies, including conservation and medical perspectives, have helped this technology become more widely applicable [18–20]. It is also regarded as a powerful tool for forecasting species expansion and measuring invasion effects. In the previous two decades, several modeling software applications based on various mathematical techniques have been developed to achieve this goal, however, Maxent (Maximum Entropy Model) is the most successful and accurate [17,21,22]. Maxent modeling is used to estimate the impact of climate change on a variety of fungi species [23]. Consequently, the present study aims to predict the global current and future distribution of *A. niger* using the geographic information system and bioclimatic variables.

2. Materials and Methods

2.1. Occurrence Data

The majority of available records for *A. niger* that reflect its distribution were collected and considered. Approximately 1000 geographical points were collected from the Global Biological Information Facility database ([GBIF.org](https://gbif.org) (accessed on 28 May 2022)). The occurrence records were subjected to three steps of filtration to prevent sample bias. First of all, duplicated records were removed. Secondly, high spatial uncertain records were eliminated. Then, spatially rarefied occurrence data was removed based on distance in ArcGIS (SDM Toolbox: SDM Tools; Universal Tools—Spatially rarefy occurrence data) [17,24]. Finally, the remaining 138 records were transformed into comma-delimited (CSV) forms and used to predict the current and future global distribution of the black mold *A. niger*.

2.2. Bioclimatic Covariates

Bioclimatic data with a spatial resolution of around 5 km² were obtained from (www.worldclim.org) (accessed on 14 May 2022). To depict the current global climate, a total of 19 climatic variables were applied, which were originally obtained from monthly

temperature and rainfall measurements collected from meteorological stations between 1950 and 2000.

For current bioclimatic covariates, fifteen bioclimatic variables were transformed into ASCII format using ArcGIS v 10.7. Due to known spatial distortions, bioclimatic layers 8–9 and 18–19 were removed [17]. To eliminate collinearity across variables, we use the Pearson correlation coefficient ($r^2 > 0.8$) to measure the correlation between each pair of covariates. Through the SDM Tools function in ArcGIS 10.7, this coefficient reduces the correlation between the covariates (Universal tool; Explore climate data; Remove highly correlated variable) [25]. Only five bioclimatic factors were chosen and utilized to create final models based on this. Annual mean temperature (Bio 1), Mean diurnal range (Bio 2), Temperature annual range (Bio 7), Annual precipitation (Bio 12), and Precipitation of the driest month (Bio 14) are the biological variables in question.

For future bioclimatic covariates, we used parallel datasets for the global climate model (GCM) from two representative concentration pathways (RCPs) 2.6 and 8.5 to account for the future distribution of *A. niger* based on carbon dioxide emission in 2050 (average of estimates for 2041–2060) and 2070 (average of predictions for 2061–2080) [26]. ArcGIS v 10.7 was used to convert these future data layers to ASCII format [25,26]. The selected variables' climatic data were then projected to the years 2050 and 2070 using the Meteorological Research Institute's global climate model (MRI-CGCM3) to analyze the effects of climate change on *A. niger* habitat suitability in the future. These statistics are part of the IPCC's Fifth Assessment Report's current GCM climate estimates.

2.3. Habitat Suitability Modeling

Maximum entropy implemented in Maxent was chosen among several software packages such as BIOCLIM, CLIMEX, and GARP [27,28]. The artificial intelligence of this algorithm produces outstanding presence-only predictive models [29]. It may also eliminate duplicate entries in the same cell, which is useful in modeling studies with limited sample sizes [29]. Consequently, Maxent v (3.4.1) was used to model the global current and future distribution of *A. niger* [29]. Our models used 75% of the occurrence records for training and 25% for testing [26,30]. There were a total of 10,000 background points and 1000 iterations [31]. In addition, 10-fold cross-validation was performed, which increased the model's performance [31].

2.4. Model Evaluation

The area under the curve (AUC) of the receiver operating characteristics (ROC) was used to measure the model's performance, which spans from 0 (random discrimination) to 1 (perfect discrimination) [17]. Poor-fitting models had AUC values less than 0.5, whereas well-fitting models had AUC values greater than 0.75 [25,26]. True Skill Statistics were also used to measure the correctness of the predicted models (TSS) [32]. TSS values varied from 0 to 1, with positive values close to 1 suggesting a strong association and negative values indicating a weak relationship between the predictive model and the distribution [32].

3. Results

3.1. Modeling Performance

For evaluating the maximum entropy model of Maxent, two statistical analyses were done: Area Under Curve AUC and True Skill Statistics TSS. The AUC value forms an effective tool to measure the modeling quality and tends to be high with perfect modeling output equal to 0.92 (Figure 1). The result indicates the high performance of the generated models. To support such an outcome, the TSS was used for the functional assessment of the model and its value of 0.7 represent a high-quality modeling process.

3.2. Contribution of Bioclimatic Variables

The five chosen climatological parameters after removing correlated variables represent the importance of temperature and relative humidity to the *A. niger* niche: Annual

mean temperature (Bio 1), Mean diurnal range (Bio 2), Temperature annual range (Bio 7), Annual precipitation (Bio 12), and Precipitation of driest month (Bio 14). The jackknife test represents the importance of each parameter in the modeling of this species (Figure 1A). The contribution of each climatological variable is shown in Table 1. The table indicates how the temperature-related variables are dominant in the habitat preference of this fungus. The annual mean temperature (bio 1) forms the most contributed climatological parameter to the model with a percentage of 36.5%. The response curve of the *A. niger* probability of percent and the Bio 1 show the range of temperature preference of this fungus between 15–30 °C (Figure 1B).

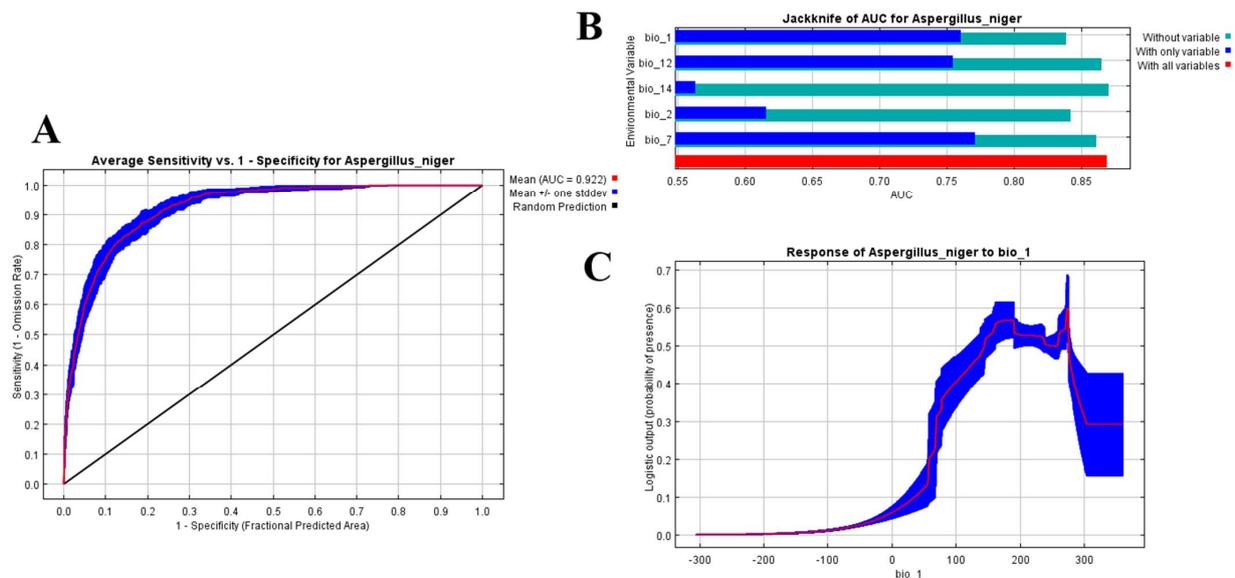


Figure 1. (A). The graph of the receiver operating characteristic (ROC) curve for the black mold data, again averaged over the replicate runs. Note that the specificity is defined using predicted area, rather than true commission (AUC = 0922); (B). The Jackknife of the main contributed variable; (C). Response curve of the most effective bioclimatic factor (bio 1).

Table 1. Relative percentages of bioclimatic variables used in Maxent to model the current and future habitat suitability of.

Bioclimatic Variables	Description	Contribution Percentages
Bio 1	Annual mean temperature	36.5%
Bio 2	Mean diurnal range	13.4%
Bio7	Temperature annual range	26.6%
Bio 12	Annual precipitation	17%
Bio 14	Precipitation of driest month	6.5%

3.3. Predicted Current Potential Distribution of Black Mold

The generated current habitat suitability map of *A. niger* indicates the wide spread of this fungus. The result has already compatible with the real situation of its distribution on the ground. Only places with very cold snowy weather or very dry hot desert areas appear free from the suitable habitat of this species, as the case in the hot Sahara Desert of the Middle East or the very cold northern parts of Russia and Canada. The other parts of the world show range of habitat suitability for this fungus. The Indian subcontinent, China and Southeast Asia form the largest part of the very high suitability areas of *A. niger*. In Africa, the Nile valley, the Eastern coasts on the Indian ocean, and the Western coasts on the Atlantic Ocean also present very high suitability. Through European countries,

the fungus has high and very high suitability especially on the southern coasts on the Mediterranean. Only the Scandinavian north appears free from *A. niger* niche. Throughout the new world, the fungus has very high to high habitat suitability on the Eastern coasts of the USA and Mexico; the same case for the Eastern coasts of South America especially on Brazil. Australian eastern coasts appear with high and very high suitability to *A. niger* invasion (Figure 2).

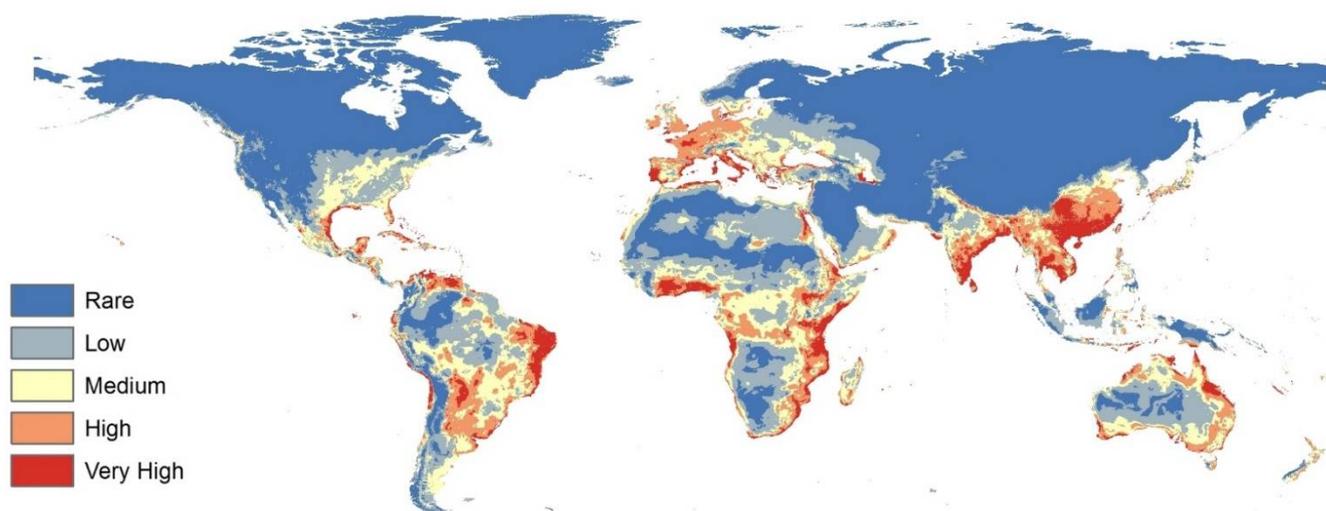


Figure 2. Current global prediction of habitat suitability for *A. niger*.

3.4. The Predicted Future Potential Distribution of Black Mold in 2050 and 2070

Four climate change scenarios were used to evaluate the shape of *A. niger* distribution response throughout the world in 2050 and 2070. The two RCPs of 2050 show great changes in the habitat suitability of this fungus throughout the globe (Figures 3A,B and 4A,B). For the best scenario of carbon dioxide emission (RCP 2.6 2050), this species gains more habitat suitability through South East Asia, the Northern India Subcontinent, and some parts of central Africa. The worst situation occurred on Europe where the habitat suitability dramatically increased throughout the continent. For the two RCPs of 2070, changes were observed for the spatial distribution of *A. niger*. For the worst climate change scenario (RCP 8.5 2070) a dramatic habitat suitability increase was observed throughout Europe and small habitat suitability loss occurred through some hot areas of the world such as the Nile Valley and part of the Amazon basin (Figures 3C,D and 4C,D).

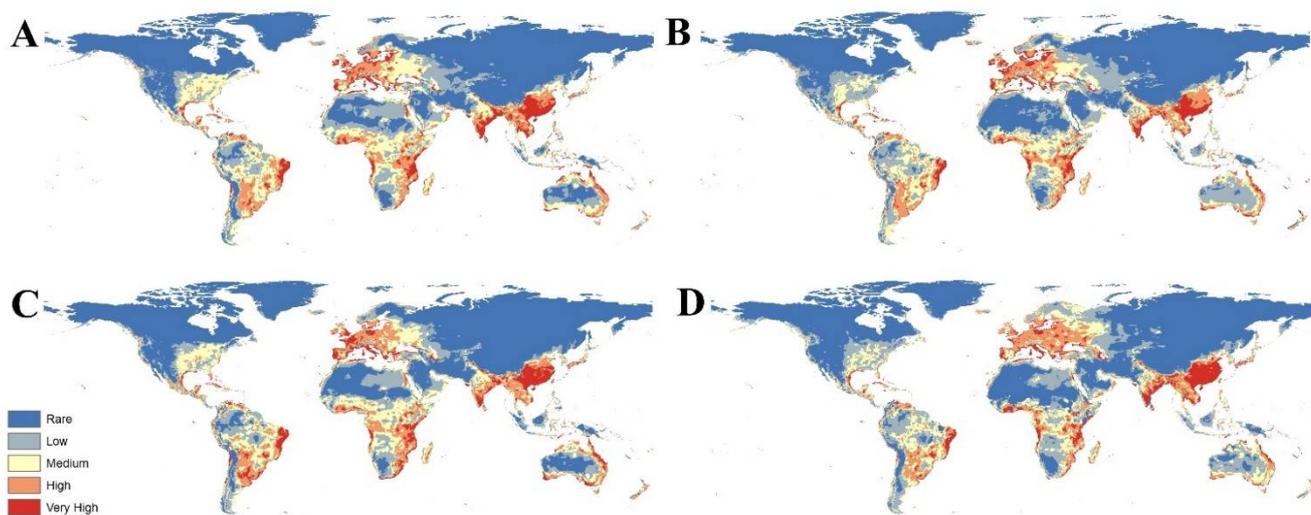


Figure 3. Prediction of global future distribution of *A. niger* under two RCPs: (A) 2050 for RCP 2.6; (B) 2050 for RCP 8.5; (C) 2070 for RCP 2.6, and (D) 2070 for RCP 8.5.

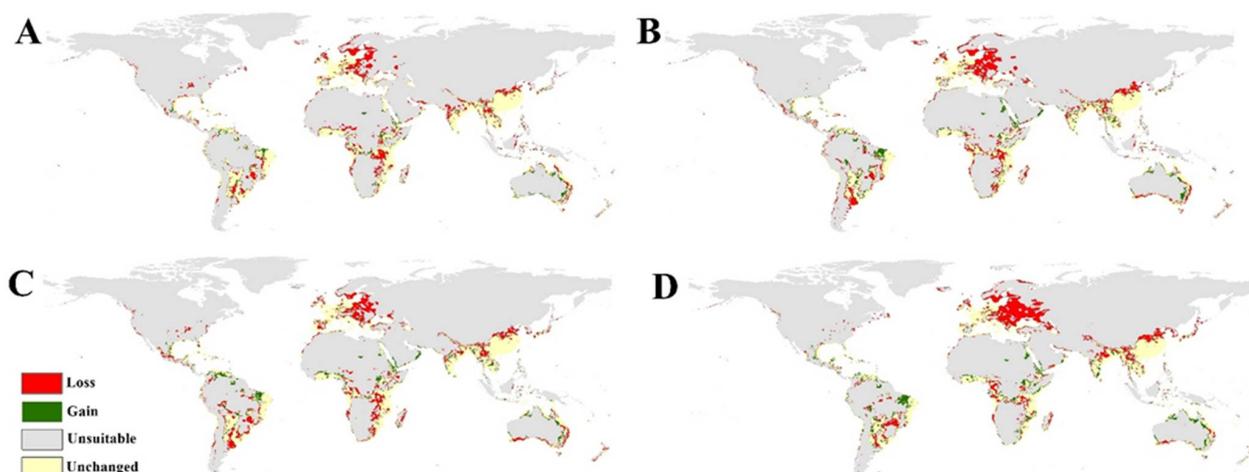


Figure 4. Calibration maps showing gain and loss in habitat suitability of *A. niger* through the four future scenarios against the current status with threshold (>0.5): (A) 2050 for RCP 2.6; (B) 2050 for RCP 8.5; (C) 2070 for RCP 2.6, and (D) 2070 for RCP 8.5.

4. Discussion

In the last few years, Aspergillosis impose as a medical emergency issue as a result of the COVID-19 pandemic and its connection as a secondary infection in many cases throughout the world [33,34]. Severe acute respiratory damage as a result of COVID-19 infection-induced pulmonary epithelium degradation enables *Aspergillus* invasion and leads to death in many cases, especially for aged patients [35]. With the wide spread of *A. niger* through the world and the continuation of COVID-19 pandemic, the need for a clear distribution map of this species becomes more urgent not only for the current situation but also for the future status under climate change.

The present work forms a step in this direction for a better understanding of the habitat requirements of *A. niger* and how it will respond to climate change. The modeling of this species of fungi was conducted by Shabani, Kumar, and Esmaeili in 2015 using CLIMEX, and only maximum and minimum temperature as parameters for the model [3]. The Maxent modeling has many advantages on CLIMEX as a modeling tool; also, the use of Bioclimatological data which implemented the connection of temperature and precipitation variables will sure improve the models' output from the previous study. The generated maxent models show a high degree of accuracy with AUC 0.92 and TSS 0.7 the number that clarifies the importance of the generated maps to evaluate the real situation of this fungus [17,20,24].

The current prediction maps of the *A. niger* indicate the cosmopolitan distribution with very few areas that are free from this fungus. The very high temperature and dryness or very cold snowy weather appear to form a limitation of this group of fungi [36]. The result shows the range of annual mean temperature preferred by *A. niger* between 15–30 °C; such a result agrees with several previous studies of its ecology [37,38]. The predicted model of current status came very similarly to the distribution range of this fungus. The Indian subcontinent, China, and Southeast Asia represent very high suitability areas for *A. niger* and the fungus has already been isolated from several environmental areas throughout the region before [39–41]. Moreover, Europe shows high and very high suitability of this fungus where it was isolated several times from different parts of the continent, including some medical cases related to COVID-19 [33,42–44]. The generated map of the current status will help workers in the health sector to evaluate the risk of Aspergillosis in weak immunized patients, including COVID-19, HIV, and edged one.

The future prediction of the *A. niger* distribution was not so far from the present situation, but the fungus makes a range shift in many areas to cope with the temperature rise. The Nile valley as an example will become free from this fungus due to an increase

in ambient temperature that will rise above the preferred range. On the other hand, the fungus will gain new habitat in several parts of the world where it will form emergence medical and agricultural issues. The case will be very clear in the Eastern part of Europe and Central Asia. In general, Climate change will be very effective on the pattern of *A. niger* distribution either on the spatial or temporal scale.

The present work forms a small step in the understanding of the biogeography of this group of fungi and its habitat. Many groups of free-living microorganisms need global evaluation using data science and geographical information system GIS techniques to help the decision-makers in preventing either medical, veterinary, or agricultural diseases.

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