Maximum entropy approach for predicting global habitat suitability of *Eleusine coracana* using a species distribution model

Introduction

The finger millet, *Eleusine coracana* L. Gaertn., is an important crop cultivated in arid and semiarid regions worldwide, especially in East Africa and India (Fakrudin *et al*. 2004). *E. coracana*, which was domesticated approximately 5,000 years ago, is inherently capable of tolerating several abiotic stressors such as water deficit and of adapting to marginal soils with low fertility (Babu *et al*., 2007). The crop is thought to have originated in Ethiopia, having been later introduced to India through sea trade around 4,000 years ago (D'Andrea *et al.,* 1999). *E. coracana* presence data was retrieved from the Global Biodiversity Information Facility (GBIF, DOI: 10.15468/dl.7cfkdi), namely 6,877 georeferenced occurrences, which spanned across south Asia, Africa and, to a lesser extent, Europe and the Americas.

Methodology

Bioclimatic variables were obtained from WorldClim v.1.4 at a 5-minute spatial resolution for present and future scenarios. Current conditions represent interpolations of observed climatic data from 1960-1990. Future climate data followed the $IPCC_5$ climate projections from global climate models (GCMs) for the 4.5 representative concentration pathway (RCP) in 2070, as estimated by the MIROC5 climate model. The following independent parameters (Spearman's rank correlation < 0.70) were selected for modelling: isothermality (BIO_3: mean diurnal range divided by temperature annual range), maximum temperature of the warmest month (BIO_5), precipitation of the wettest month (BIO_{13}), and precipitation of the driest month (BIO_{14}). The variable selection aimed to closely capture the extreme heat, drought and fire resistance displayed by the finger millet across its range (Givnish *et al.*, 2010).

Species Distribution Models (SDMs) were constructed for current and future bioclimatic variables of *E. coracana* using MaxEnt v.3.2.18 (Phillips *et al.,* 2006). MaxEnt estimates species distributions by finding the distribution of maximum entropy, or the closest to uniform, subject to the constraint that the expected value of each bioclimatic variable under the estimated distribution matches its empirical range (Phillips *et al.,* 2006). The set maximum entropy parameters were the random test percentage as zero, the maximum number of background points as 10,000, and the regularisation multiplier as 1, for which five bootstrap replicates were run.

Model output

Predicted distribution models of *E. coracana* were attained for present climatic conditions (Figure 1) and the predicted scenario for the year 2070 under the RCP 4.5 (Figure 2). The models provide the probability of occurrence of the finger millet worldwide, based on the four selected bioclimatic variables.

Predicted highly suitable habitat for the finger millet under present bioclimatic conditions occurred mainly in East Africa and India, as expected given the intense exploitation of the crop in these areas. Moreover, high suitability was pinpointed in other regions of the globe such as southern North America, western and eastern South America, China, eastern Australia, New

Zealand, and western Europe. Elevated habitat suitability can be observed in the Andes (South America), the Drakensberg (South Africa), the Australian Alps (Australia), and the Sierra Madre (Mexico) mountain ranges; these probably represent extrapolations from the altitude-resistant strains cultivated in the Himalayas, given the subsequent colonisation of this mountain range after the introduction of the species in India (D'Andrea *et al.,* 1999). Nonetheless, the adequate predicted conditions displayed across western Europe do not seem to pair with the biological requirements of the species, and potentially display a bias of the model towards the rare European presence data used in the training set.

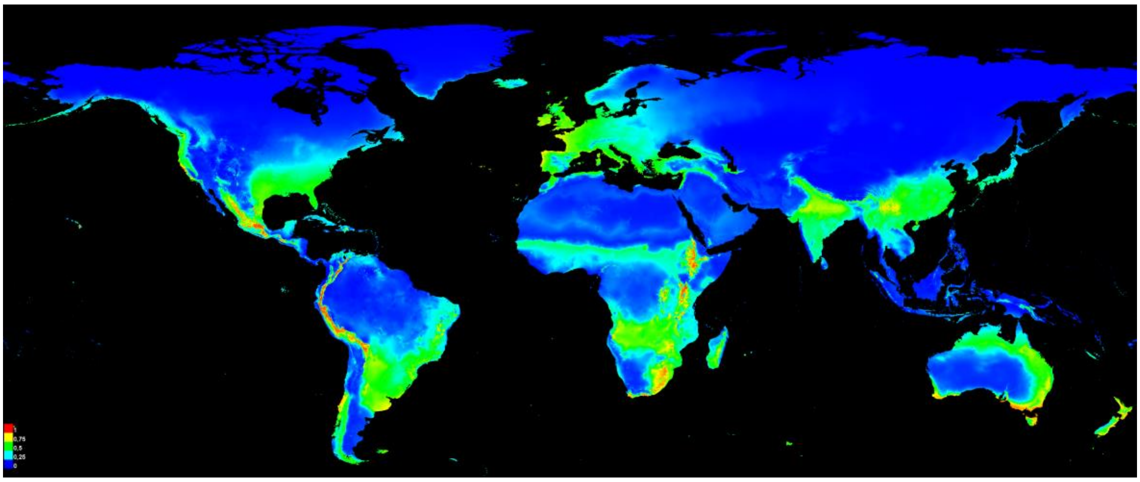

Figure 1: Global suitability of *E. coracana* for current climatic conditions. Warmer shading colours represent areas where the probability of occurrence is higher.

The predicted global suitability of finger millet for 2070 largely mimics its current habitat suitability, when examining the probability of occurrence worldwide. Thus, under the RCP 4.5 scenario for 2070, climate change does not seem to have a strong effect on the distribution of *E. coracana*. The similarity between the models, despite the over 50-year difference, could be explained by the heat resistance displayed by this cereal, seemingly unaffected by the increasing temperatures brought by climate change. Other factors could be shaping its potential range; for instance, light availability could be influential, as it has partly driven the evolution of the PACMAD-BEP clade to which the finger millet belongs to (Givnish *et al.,* 2010).

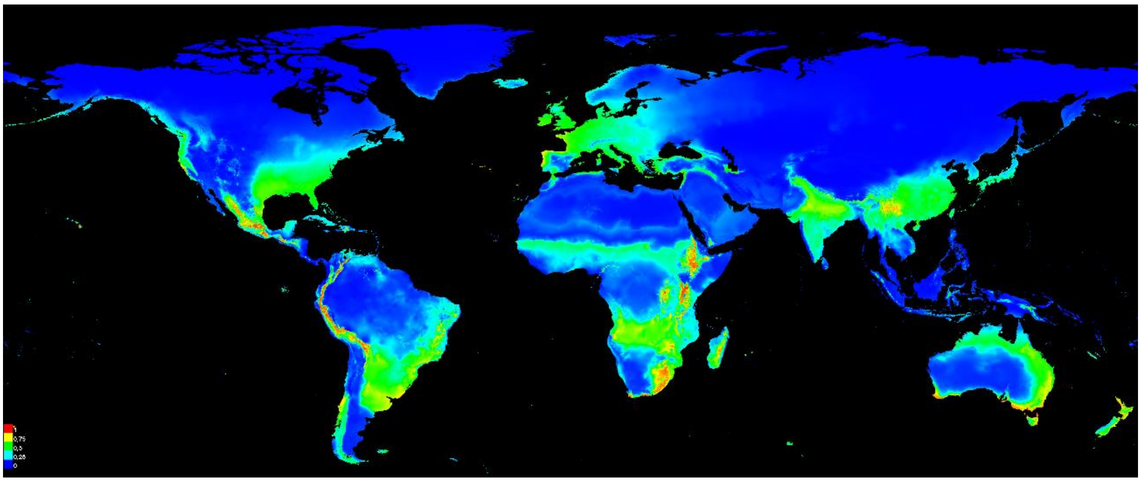

Figure 2: Global suitability of *E. coracana* for predicted climatic conditions in 2070 under the RCP 4.5. Warmer shading colours represent areas where the probability of occurrence is higher.

Model accuracy was given by the Area Under the Curve (AUC) value of 0.872 (SD ± 0.003), which preliminarily indicates a good fit. Given the model predicts highly suitable areas being in already cultivated zones and in mountainous areas, the apparent good fit of the model could be justified. However, the potentially erroneous identification of Europe as favourable habitat for *E. coracana* could point towards a bias in the model.

The maximum entropy analysis indicated isothermality and the maximum temperature of the warmest month are driving the distribution patterns of *E. coracana* (Table 1). The large contributions of both temperature variables is intuitive, given the high optimal growth temperature of the species, which is prevalent in arid and hot areas (Babu *et al.,* 2007). Precipitation parameters were deemed relatively unimportant to the spatial patterns of the finger millet, probably due to the drought-resistance associated to this crop (Dida *et al.,* 2008).

Variable	Percent contribution	Permutation importance
BIO_3: Isothermality	52.5	21.6
BIO_5: maximum temperature of the warmest month	39.7	29.5
BIO_{14}: precipitation of the driest month	4.7	14.8
BIO_{13}: precipitation of the wettest month	3	34

Table 1: Estimates of the relative contributions of the bioclimatic variables to the MaxEnt model.

Response to future scenario

The differences in habitat suitability when comparing present and future conditions display the overall continuity of ideal areas through time (Figure 3). There appears to be an approximately equal gain and loss in suitable zones, distributed across the margins of the currently suitable areas.

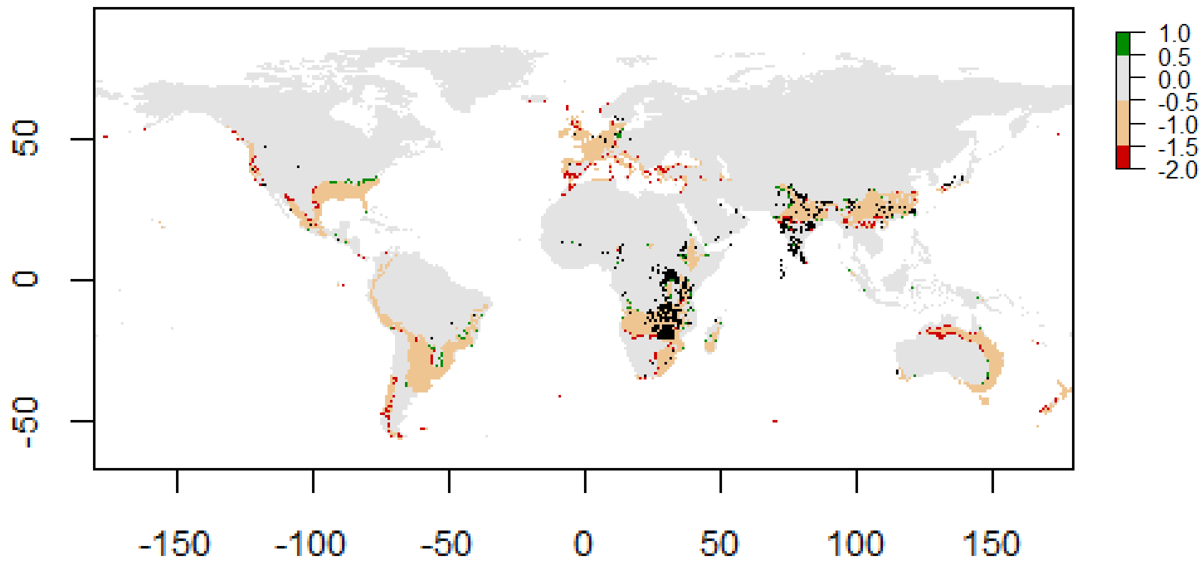

Figure 3: Differences in habitat suitability for *E. coracana* between present and future bioclimatic conditions at occurrence scale. Grey are unsuitable areas both in present and future, khaki are areas that remain suitable, green represents areas gained, and red are areas lost. Black dots indicate presence data downloaded from GBIF.

Biological interpretation

The climate envelope of the finger millet is much larger than its current distribution, potentially revealing areas where the crop could be successfully exploited. Climate change does not seem to dramatically affect the distribution of *E. coracana*, given the majority of the suitable areas remain so, and there is a predicted balance between gained and lost areas. The sustained global suitability of the crop, despite climate change associated temperature increases, could pose relevant information for farmers and governments in the planning of future agrarian policies. The species shows a high degree of tolerance to varying environmental conditions, portrayed by the altitude and heat resistance in the model, potentially driving its success when facing climate change.

The maximum entropy model generated for *E. coracana* appears to be useful in predicting suitable habitats and displaying the behaviour of the crop when faced with climate change. The predictions should be interpreted cautiously as the European niches could represent a bias, and because the suitability of the Himalayas, where the species arrived approximately 4,000 ago, does not necessarily mean it would readily adapt to other mountain ranges. Careful curation of the presence data, along with increased presence occurrences, would be necessary in order to produce more reliable model predictions avoiding any possible sampling bias.

References

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