Section THREE

The distribution of *Boswellia* species

When considering the conservation and sustainable use of any species, knowing where it occurs is information fundamental to a range of analyses and subsequent actions. These can include conservation assessments at global and regional scales, species modelling in cases where detailed fieldwork across wide ranges is impractical as is the case with many widespread plant species, and modelling distribution in both the contemporary and future senses against climate change predictions. It also allows comparisons of whether species are well represented in conservation programmes including Protected Areas, and how these might protect species and habitats in the future.

Recent years have seen the establishment of a range of resources designed to make distribution data accessible globally for many of the above-mentioned purposes. The largest is the Global Biodiversity Information Facility (https://www.gbif.org/) which holds vast arrays of data from a wide range of sources. However, data held within GBIF is of various types that can require detailed sorting, contains errors often resulting from mistakes at the submitting organisation, and is also somewhat geographically biased: there are many countries that contribute very little data, and information about biodiversity in those areas is most often that held at institutions in other areas. These geographical biases can often be due to resource limitations. There are a number of examples within *Boswellia* where data about a particular specimen is entered several times on GBIF with differences of data quantity and quality between entries.

When considering a small genus of plants such as *Boswellia*, there is much data held in small institutions, published literature and also unpublished matter that is not available in global systems. Further, stakeholders interested in *Boswellia* are of different types and may not have access to the skills required to sift through data held in global data repositories. In such cases, gathering data in a single location that suits the varied users can be beneficial, even if that data is subsequently submitted to GBIF and the errors within it are corrected (which can in itself be a complex undertaking).

With the current focus on the sustainable use and trade in *Boswellia* products, it was decided to start the process of gathering as much accurate distribution data about *Boswellia* species to enable some of the abovementioned activities to augment that held in global repositories, and to ensure all data is accurate.

Section 3.1

Distribution records

This process focused first on geo-referenced herbarium voucher specimens. These specimens are the only type of data that is robust in the face of taxonomic change as they can be examined and re-determined as necessary. Therefore, data on herbarium specimens of all species of *Boswellia* was gathered from a variety of sources: published literature, online herbarium databases, and by contacting all herbaria in *Boswellia* range States as these often house specimens that are not available on global resources yet can have a significant impact on the amount of data available for specific taxa (Delves *et al* (2023). A large proportion of data gathered was taken directly from herbarium specimens to ensure accuracy. In total, 214 herbaria were contacted directly in this exercise (59 from range States, 121 additionally from

India, 34 global herbaria). More than 40 herbaria in range States did not respond to requests for information.

The total number of unique specimens acquired is 1606 (2091 including duplicates) and is given by species in Table 3.1. This more than doubles the number of specimens cited in Thulin (2020). A full list of voucher specimens added to the database is given in Appendix 3.1.

All voucher specimens were geo-referenced manually where possible. Examples of when this was not possible include situations where minimal data was available from the specimen itself, for example if the only information gathered was the name of the species and the country in which it was collected, with the caveat that the latter may have changed since collection due to changes in State boundaries. A specific example of this occurs with herbarium specimen Aubreville 2197 which was collected in 1935 as *B. dalzielii* by the Forest Service of Cote d'Ivoire. This specimen is cited on GBIF as being collected in Cote d'Ivoire and has subsequently been cited in many publications, databases and websites, and the occurrence of *B. dalzielii* in Cote d'Ivoire assumed to be accurate. However, examination of the specimen reveals an annotation that states "Haute Volta" – translated to "Upper Volta" which was previously the title of the State of Burkina Faso. Thulin (2020) pointed out that this specimen was likely collected in Burkina Faso and as such *B. dalzielii* has never been collected in Cote d'Ivoire.

Secondly, online databases and published literature was consulted to collate additional distribution records from field surveys and from literature records. No assumptions were made about broad vegetation surveys – if a species of *Boswellia* was not specifically annotated as occurring in a certain location then no record was added to the database. Many such records were gathered from literature reporting on a variety of studies, but which gave collection coordinates for that particular species. These records, while valuable, are treated as secondary in nature to voucher specimens as (a) they may have been incorrectly identified and there is no way to check, and (b) they cannot be redetermined following taxonomic changes. Additional field data held at RBGE was derived from associated taxa noted at the time of the collection of a particular specimen. Realistically, where a single species occurs in isolation and no other species of *Boswellia* are known or likely to overlap in distribution, such records can be considered accurate, an example being *B. sacra* in the Arabian Peninsula where no other species of *Boswellia* has ever been recorded. The same occurs for many States in west Africa that harbour *B. dalzielii*.

The total number of field and literature records gathered to date is 1499 and is given species by species in Table 3.2. A full list of these records with their references is given in Appendix 3.2. No additional records of Soqotra endemic species have been added: an extensive survey programme has been completed on Soqotra by a research team from Mendel University in Brno, Czechia and these data may be acquired at a later date. The only two species without additional field and literature records otherwise are *B. microphylla* (as this has routinely been collected as *B. neglecta* and not studied or surveyed independently) and *B. ovalifoliolata* which is a narrow endemic from India.

All occurrence records have been input into the database and their source (voucher, field, literature) and reference added.

At this stage, no records on global databases derived from photographic records have been included in this data set as the key characters for identification are often not visible so verification is problematic. Even where a single species occurs in a single State, sterile specimens can be mistaken for different genera in some cases.

It is expected that both sources of distribution records will increase in number as additional sources are published or unveiled, or where additional collections in herbaria are identified and added.

The contemporary distribution of all 24 species of *Boswellia* can be viewed on the Frankincense Resource Portal. At the time of writing, the maps visible are based upon verified herbarium specimens only. Field and literature records will be added to maps and colour coded so that different types of records can be distinguished.

Species	**# specimens**
Boswellia ameero	40
Boswellia aspleniifolia	27
Boswellia bullata	20
Boswellia dalzielii	337
Boswellia dioscoridis	17
Boswellia elongata	60
Boswellia frereana	105
Boswellia globosa	5
Boswellia “hesperia”	0
Boswellia microphylla	139
Boswellia nana	11
Boswellia neglecta	366
Boswellia occulta	5
Boswellia ogadensis	13
Boswellia ovalifoliolata	15
Boswellia papyrifera	246
Boswellia pirottae	25
Boswellia popoviana	25
Boswellia rivae	120
Boswellia sacra	190
Boswellia samhaensis	2
Boswellia scopulorum	3
Boswellia serrata	248
Boswellia socotrana	42
Boswellia sp.	30
Total (including duplicates)	**2091**

Table 3.1 Number of herbarium specimens by species acquired. Boswellia sp. indicates sterile specimens difficult to identify to species.

Section 3.2

Species Distribution Modelling

In order to complete conservation assessments, assess coverage in Protected Areas, and locate suitable areas for cultivation and management, as well as locating potential areas of distribution outside those areas already known but possibly overlooked, it was decided to use Species Distribution Modelling (SDM) for those taxa for which it is amenable. Species distribution modelling can be a useful tool for understanding the environmental tolerance of a species and how this relates to its geographic range, and its distribution within that range.

The main purpose of SDM within this project was to explore the potential range of nine *Boswellia* species outside of their current known extent of occurrence. This requires a minimum number of discrete location points – often cited as at least ten but in reality, a minimum of 20 is ideal. Of the 24 *Boswellia* species currently described, SDM is currently inappropriate for several of them: these include 11 species from Soqotra as the topography of Soqotra is extremely complex and variable over short distances and climate models do not represent orographic rain and fog that are critical in determining their distribution, and also several other narrow endemics where very few verified distribution points are available to build robust models from associated environmental data (*B. globosa*, *B. occulta*, *B. ogadensis*, *B. ovalifoliolata*, The remaining nine species are amenable to modelling.

The nine species selected for modelling were chosen based on the availability of occurrence records (i.e. sufficient for the model to be able to adequately define the environmental niche), and the availability of corresponding environmental data at an appropriate resolution for the geographic area of interest. The resulting maps of modelled distribution have multiple applications, e.g. calculation of predicted extent of occurrence for use in IUCN Red List assessments, guiding the direction of systematic field surveys to search for new populations in under-studied areas, examining potential habitat loss (in conjunction with historical land use/land cover change data), or to explore potential range shifts under different climate change scenarios. Several range States have indicated they would be interested to see actual, potential and future distribution models for *Boswellia* species in relation to current and proposed Protected Areas.

Methods

We used Maxent (Phillips, Dudík, & Schapire, 2018) for SDM, a machine-learning method specifically designed for use with museum and herbarium data (i.e. presence-only datasets), that has repeatedly outperformed other types of model based on predictive accuracy (Merow *et al.,* 2013). It estimates the target distribution of a species by finding the distribution of maximum entropy; that which is closest to uniform across environmental space. Maxent requires occurrence point data (e.g. herbarium records) and environmental raster data (e.g. climate, elevation, geology).

Occurrence data were gathered for each species from a variety of sources. Records were mapped to check for potential locality errors, and these were corrected and manually georeferenced where possible by examining locality text on specimen labels and/or any corresponding literature. Where feasible (and particularly important for records that appear to be outliers), herbarium specimens were examined in person or via scanned images available online to verify the current species determinations.

The distribution of records was examined to determine if the data needed to be thinned (i.e. multiple points in close proximity to each other) in relation to the resolution of the environmental data (see below), while also considering potential spatial bias in data, and whether or not locally dense records were likely to be a reliable representation of the natural distribution of each species, or were a factor of collecting bias. The final number of occurrence records used to build and train the model for each species is shown in Table 3.3.

Species	**# specimens**
Boswellia ameero	
Boswellia aspleniifolia	
Boswellia bullata	
Boswellia dalzielii	235
Boswellia dioscoridis	
Boswellia elongata	
Boswellia frereana	13
Boswellia globosa	1
Boswellia "hesperia"	
Boswellia microphylla	
Boswellia nana	
Boswellia neglecta	3
Boswellia occulta	12
Boswellia ogadensis	3
Boswellia ovalifoliolata	
Boswellia papyrifera	1001
Boswellia pirottae	12
Boswellia popoviana	
Boswellia rivae	8
Boswellia sacra	63
Boswellia samhaensis	
Boswellia scopulorum	
Boswellia serrata	149
Boswellia socotrana	
Total	**1499**

Table 3.2 Number of field and literature records by species acquired.

Species	Records
B. dalzielii	97
B. frereana	17
B. microphylla	56
B. neglecta	136
B. papyrifera	69
B. pirottae	20
B. rivae	49
B. sacra	72
B. serrata	69

Table 3.3. Number of verified records used for SDM for nine species of *Boswellia*.

For most *Boswellia* species, their environmental niche is not well understood. For these preliminary models, we chose to focus on climate data. For all species we used 19 climate variables from the CHELSA (Climatologies at high resolution for the earth's land surface areas – see https://chelsa-climate.org/) dataset. CHELSA data were downscaled from coarse climatic reanalysis data (data from weather stations combined with climate models) and were developed to resolve issues in areas where there are low densities of weather stations, and/or complex topography. It provides average climatic conditions from 1979 – 2013 and is available at a resolution of 30 arc seconds (c. 1km x 1km). High resolution data were selected for this study as they produce better predictions for plants than data at coarser resolutions (Guisan & Thuller, 2005). As the purpose was to investigate potential range beyond known extent of occurrence, and little is known about the dispersal capabilities of these species, we used a large geographic extent for environmental data. For *B. dalzielii, B. frereana, B. microphylla, B. neglecta, B. papyrifera, B. pirottae, B. rivae and B. sacra* the selection of background points (i.e. characterisation of the environment) was confined to a bounding box covering the entire African continent and the Arabian Peninsula. For *B. serrata* the extent was confined to India & bordering countries, and Sri Lanka.

We used default settings in Maxent which included auto features, 10,000 background points, a maximum of 500 iterations, and a default prevalence of 0.5. Default settings were originally developed based on performance across a range of taxonomic groups (Phillips & Dudík, 2008). These settings consistently produced the best predictive performance across all *Boswellia* species. Within-model testing was carried out using 20 replicate runs with cross validation. Replication allows Maxent to run a series of analyses that assist in evaluating the predictive performance of each model. We examined the analysis of omission/commission graph, the receiver operating characteristic (ROC) curves and associated AUC (area under the curve) value, with the following guidelines for interpreting the AUC statistic: excellent (0.90 - 1.00), very good (0.8 - 0.9), good (0.7 - 0.8), fair (0.6 - 0.7), and poor (0.5 - 0.6) (Ren-Yan *et al.*, 2014 and references therein).

The logistic output from the Maxent model is a raster of probability values (the probability of presence based on suitable environmental conditions) across the area of interest. These maps were reclassified using the ten-percentile training presence threshold. The minimum training presence threshold value is the lowest probability value for any pixel that contains an actual presence record. In ecological terms the value can be interpreted as representing the probability of presence where the environmental conditions are least suitable for the species (Pearson *et al.,* 2007). The ten-percentile training presence threshold value takes this a step further by excluding the lowest 10% of the probability values associated with occurrence records. In addition to providing a more conservative estimate of the potential distribution of a species, it serves as an additional means to address error in the dataset because it excludes occurrence records that are outliers.

Maxent also generates analyses that provide insight into the importance of each environmental variable in terms of its individual contribution to the fit (or gain) of the model. To assess which variables mattered most to the distribution of each species we examined the analysis of variable contributions, Jackknife training and test gain graphs, and Jackknife AUC graphs.

Results

Maps are presented below for each of the nine modelled species, with associated comments. Modelled maps are also presented on the Frankincense Resource Portal.

For all African species except *B. rivae*, and for the Arabian records of *B. sacra* (when modelled separately) the analysis of variable contributions indicates that bio4 (temperature seasonality) is the most important climatic variable. The most important climatic variable for *B. serrata* is unclear and requires further investigation.

B. pirottae (see section 3.6) and *B. frereana* (see section 3.2) were the two species that had the lowest number of records. However, predictive performance (based on AUC values) was excellent for both.

Order of importance	Variable code	Variable name	Explanation
1	bio 4	temperature seasonality	Standard deviation of the monthly mean temperatures
2	bio 7	annual range of air temperature	The difference between the Maximum Temperature of Warmest month and the Minimum Temperature of Coldest month.
3	bio 3	isothermality	Ratio of diurnal variation to annual variation in temperatures
4	bio 8	mean daily mean air temperatures of the wettest quarter	The wettest quarter of the year is determined (to the nearest month).
4	bio19	mean monthly precipitation amount of the coldest quarter	The climate moisture index of the month with the highest precipitation surplus.
5	bio11	mean daily mean air temperatures of the coldest quarter	The coldest quarter of the year is determined (to the nearest month).
5	bio12	annual precipitation amount	Accumulated precipitation amount over 1 year.
5	bio18	mean monthly precipitation amount of the warmest quarter	The warmest quarter of the year is determined (to the nearest month).
6	bio16	mean monthly precipitation amount of the wettest quarter	The wettest quarter of the year is determined (to the nearest month).
7	bio1	mean annual air temperature	mean annual daily mean air temperatures averaged over 1 year.
8	bio9	mean daily mean air temperatures of the driest quarter	The driest quarter of the year is determined (to the nearest month).
8	bio15	Precipitation seasonality	The Coefficient of Variation is the standard deviation of the monthly precipitation estimates expressed as a percentage of the mean of those estimates (i.e. the annual mean).
8	bio17	mean monthly precipitation amount of the driest quarter	The driest quarter of the year is determined (to the nearest month).
9	bio10	mean daily mean air temperatures of the warmest quarter	The warmest quarter of the year is determined (to the nearest month).
10	bio5	mean daily maximum air temperature of the warmest month	The highest temperature of any monthly daily mean maximum temperature.
11	bio6	mean daily minimum air temperature of the coldest month	The lowest temperature of any monthly daily mean maximum temperature.
12	bio14	Precipitation amount of the driest month	The precipitation of the driest month.
13	bio2	mean diurnal air temperature range	Mean diurnal range of temperatures averaged over 1 year.
13	bio13	Precipitation amount of the wettest month	The precipitation of the wettest month.

Table 3.4. The most important climate variables across all nine species based on examination of Maxent analysis of variable contributions (jackknife of regularized training gain, jackknife of test gain, and jackknife of AUC). Variables are ranked in order of importance. Bio4, Bio2 and Bio3 are highly correlated and two of these could be removed to simplify the models. Explanation of variables is from CHELSA V2.1 Technical Specifications. Available to download at https://chelsa-climate.org/downloads/

Boswellia dalzielii

SDM predicts this species predominantly in areas it is already known from. When including additional field records, it is predicted to occur with a high probability in the extremities of States where it has not been formally recorded including parts of northeastern Guinea and western Libera, and with relatively low probability in parts of Ivory Coast, CAR, Chad, Gabon, Sudan and South Sudan (see Figure 3.1). There are occurrence records in Niger that do not appear to be accurately predicted by the model. These require further investigation. Otherwise, the model appears accurate compared to locations of existing records.

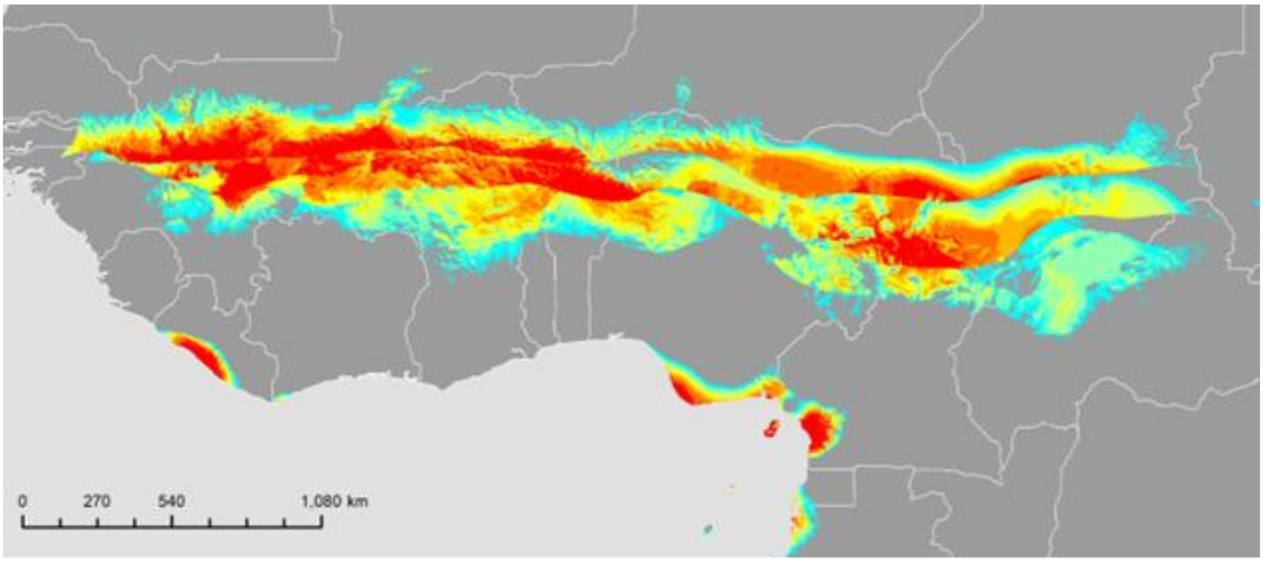

Figure 3.1. Modelled current distribution of *B. dalzielii*.

Boswellia frereana

Figure 3.2 shows high probability values in areas that this species is already known from. A few locations of relatively high probability in both Arabia (not surprising, as it overlaps with *B. sacra* in Somalia which has a similar climate to Arabian populations of the latter but clearly did not disperse there), and in Eritrea (same reasons and unlikely occurrence – although why it has not dispersed there requires explanation).

Figure 3.2. Modelled current distribution of *B. frereana*.

Boswellia microphylla

The model (Figure 3.3) accurately predicts observed distribution but also suggests this species may occur further south in Kenya. This may be due to misidentification of field records as *B. neglecta* during previous taxonomic complexity. Further investigation is required as to why it is predicted to occur on the west of Soqotra while other taxa are not (including the overlapping *B. neglecta* and *B. rivae*).

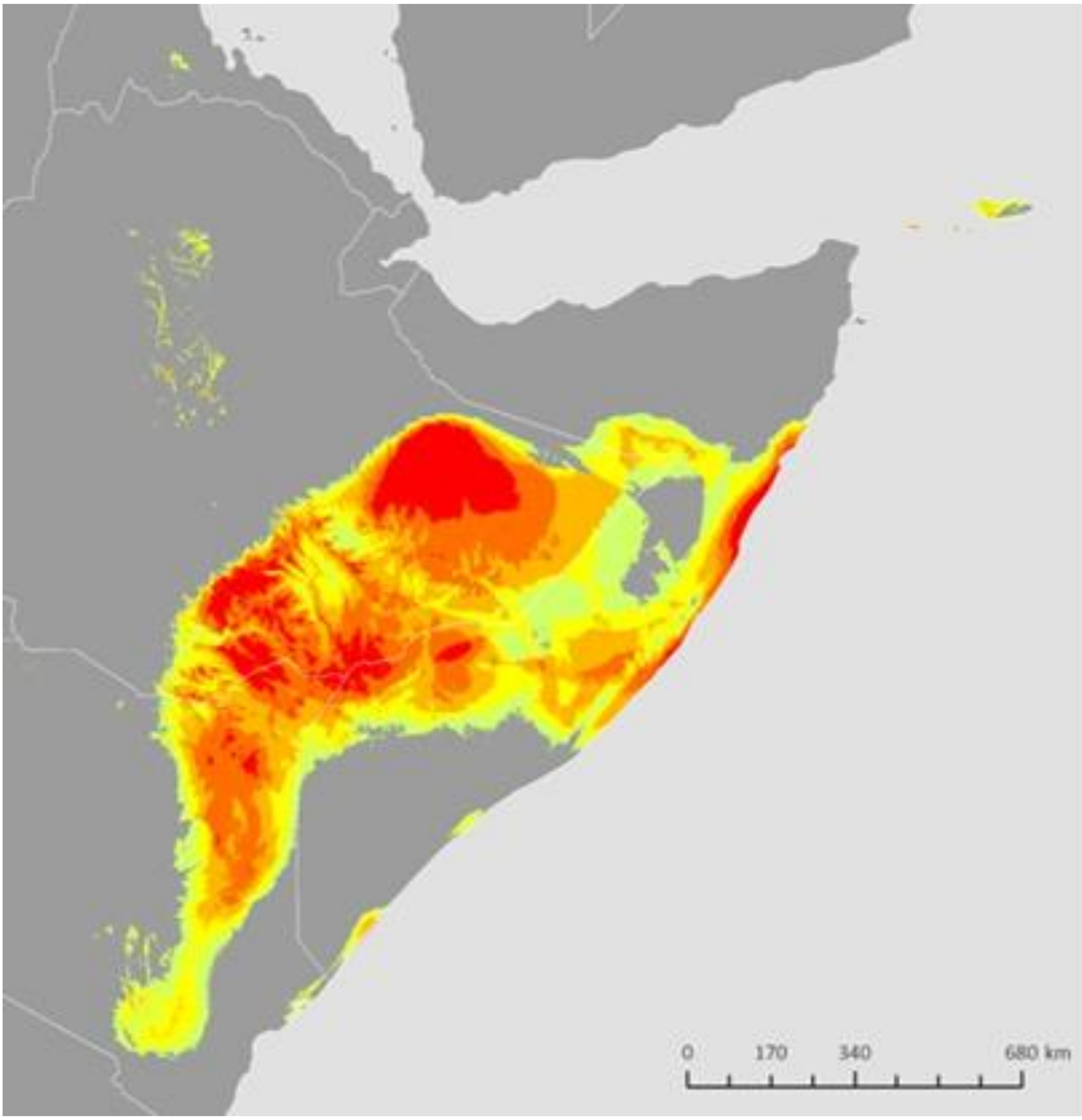

Figure 3.3. Modelled current distribution of *B. microphylla*.

Boswellia neglecta

The model (Figure 3.4) accurately predicts observed distribution in most areas, with the exception of two records in Somalia and two in Ethiopia. These require further investigation. The predicted distribution of this species clearly overlaps with *B. microphylla* but extends farther south and west which requires explanation. Predicted distribution towards the south of Tanzania is likely explained by a single occurrence record in that area which is something of an outlier in relation to other data points. This also requires further investigation.

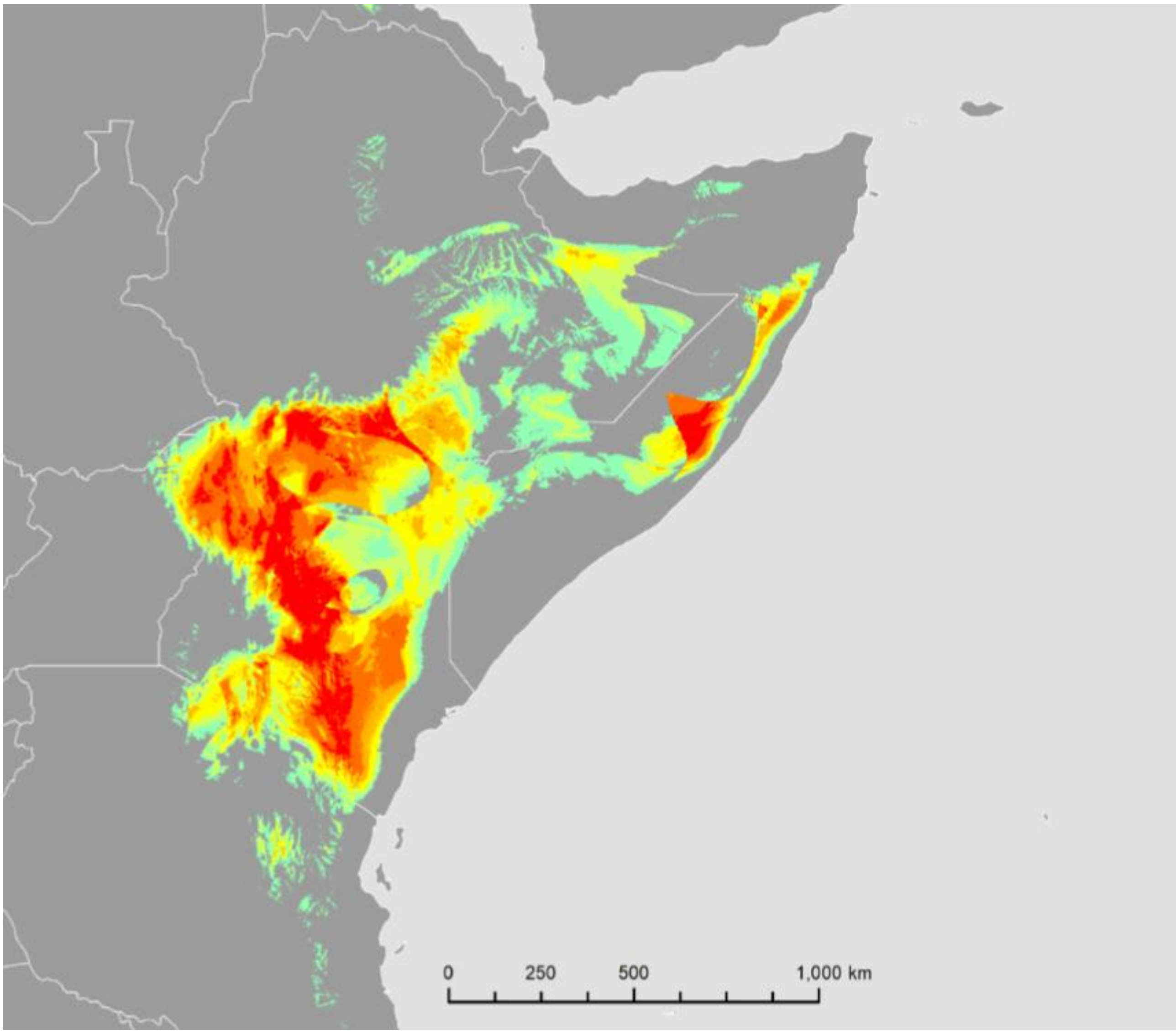

Figure 3.4. Modelled current distribution of *B. neglecta*.

Boswellia papyrifera

Occurrence records suggest a very patchy distribution and one that is not contiguous across the modelled range shown here (Figure 3.5). The model suggests high probability in some areas where there are no occurrence records (e.g. Angola, northern Tanzania and Kenya). There are low probability values in northern Cameroun where there are a cluster of occurrence records. This may be due to misidentifications or hybrids with *B. dalzielii* in that it overlaps in Cameroun and Nigeria with *B. dalzielii*, and as such some specimens and several field records may be misidentifications which would lead to inaccurate distribution predictions. The model for this species extends the potential occurrence into west Africa, and further work is required to untangle whether this is due to misidentifications or not.

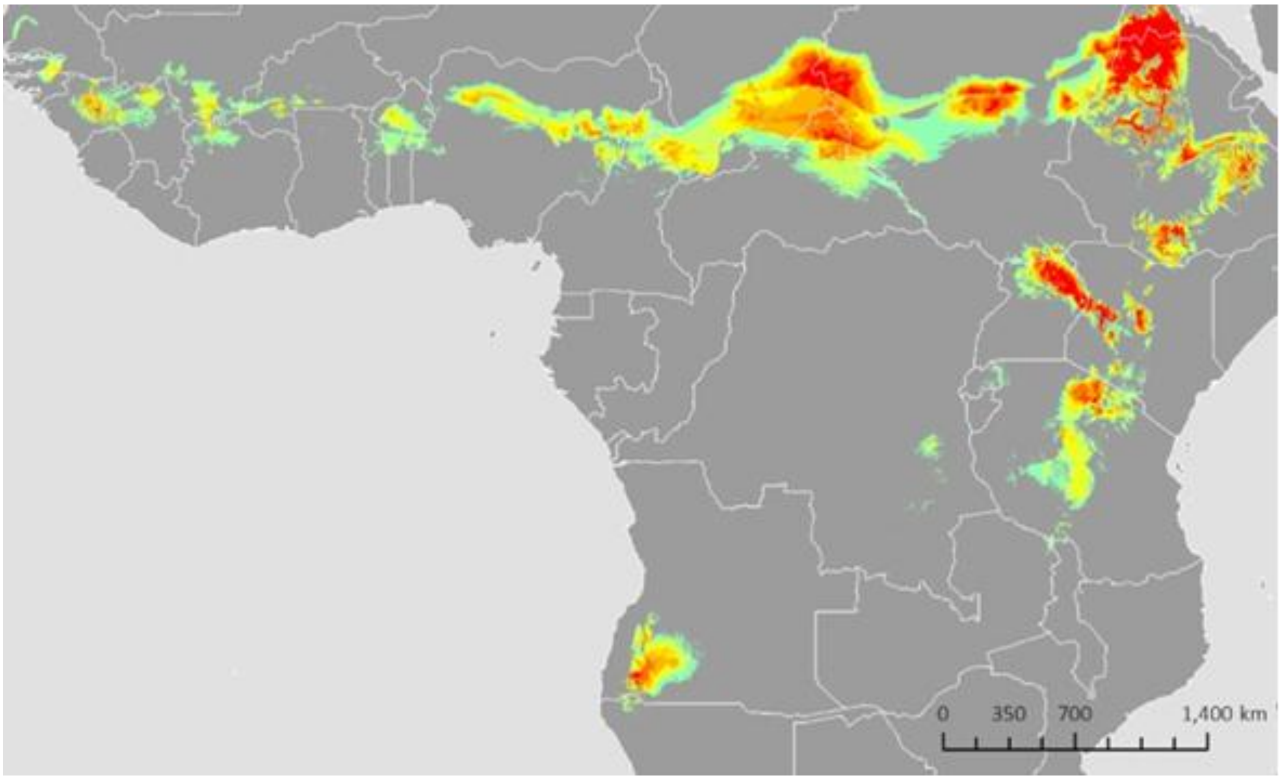

Figure 3.5. Modelled current distribution of *B. papyrifera.*

Boswellia pirottae

The model predicts the core of known occurrences in Ethiopia accurately, with high probability values extending up to the border with Eritrea (Figure 3.6). There is a record close to the southeastern border of Sudan that corresponds to a low probability value (i.e. below the threshold) that requires further investigation. While it appears that similar suitable environmental conditions exist in West Africa, finding the species there seems implausible.

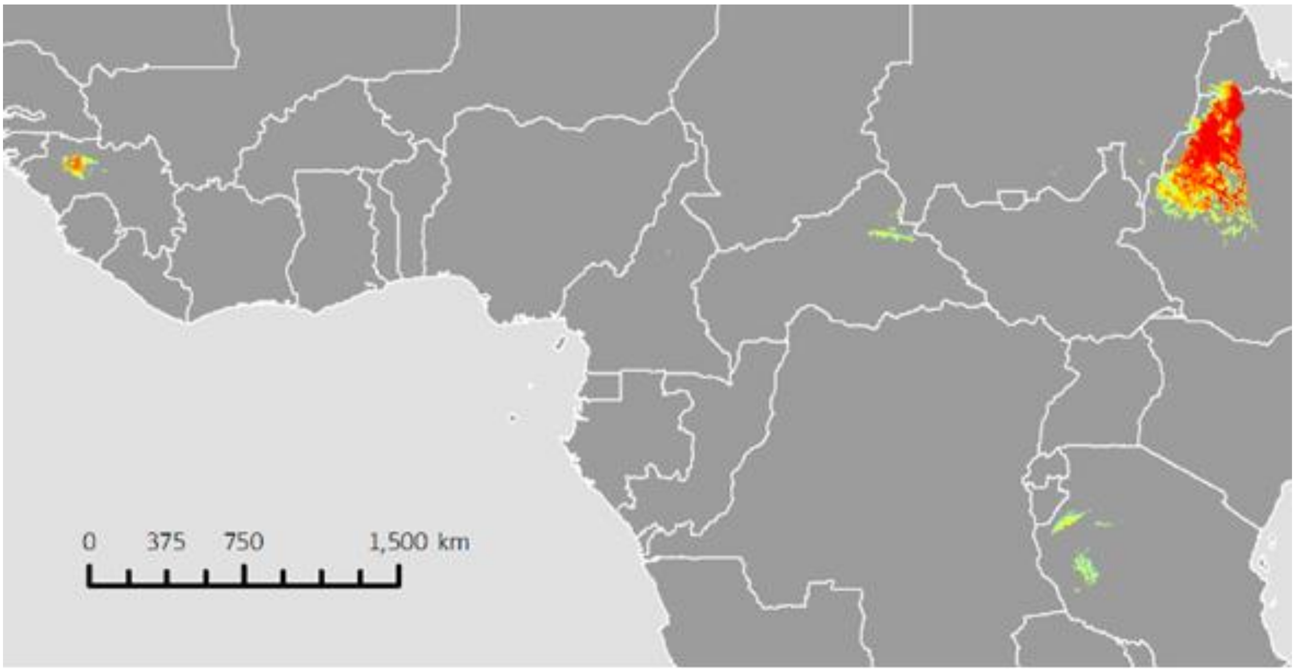

Figure 3.6. Modelled current distribution of *B. pirottae.*

Boswellia rivae

The modelled distribution for this species (Figure 3.7) appears reasonably accurate when compared to the observed distribution. There are three records in Ethiopia that are not covered by the model and one in Somalia. These require further investigation. Other than an extension of range into Kenya, the model does not show any high probability values for new areas (i.e. where the species has not already been observed).

The modelled range shows overlap with *B. microphylla* and *B. neglecta*. These three species share some similarities and are those that are not cut for resin harvest but collection is from natural exudates. The fact that their distributions overlap so much requires further investigation to work out what is keeping these taxa as separately evolving species. While the differences between them are relatively clear, little work has been done on their resin chemistry and as naturally sustainable harvesting systems they have great potential for economic benefit for local communities.

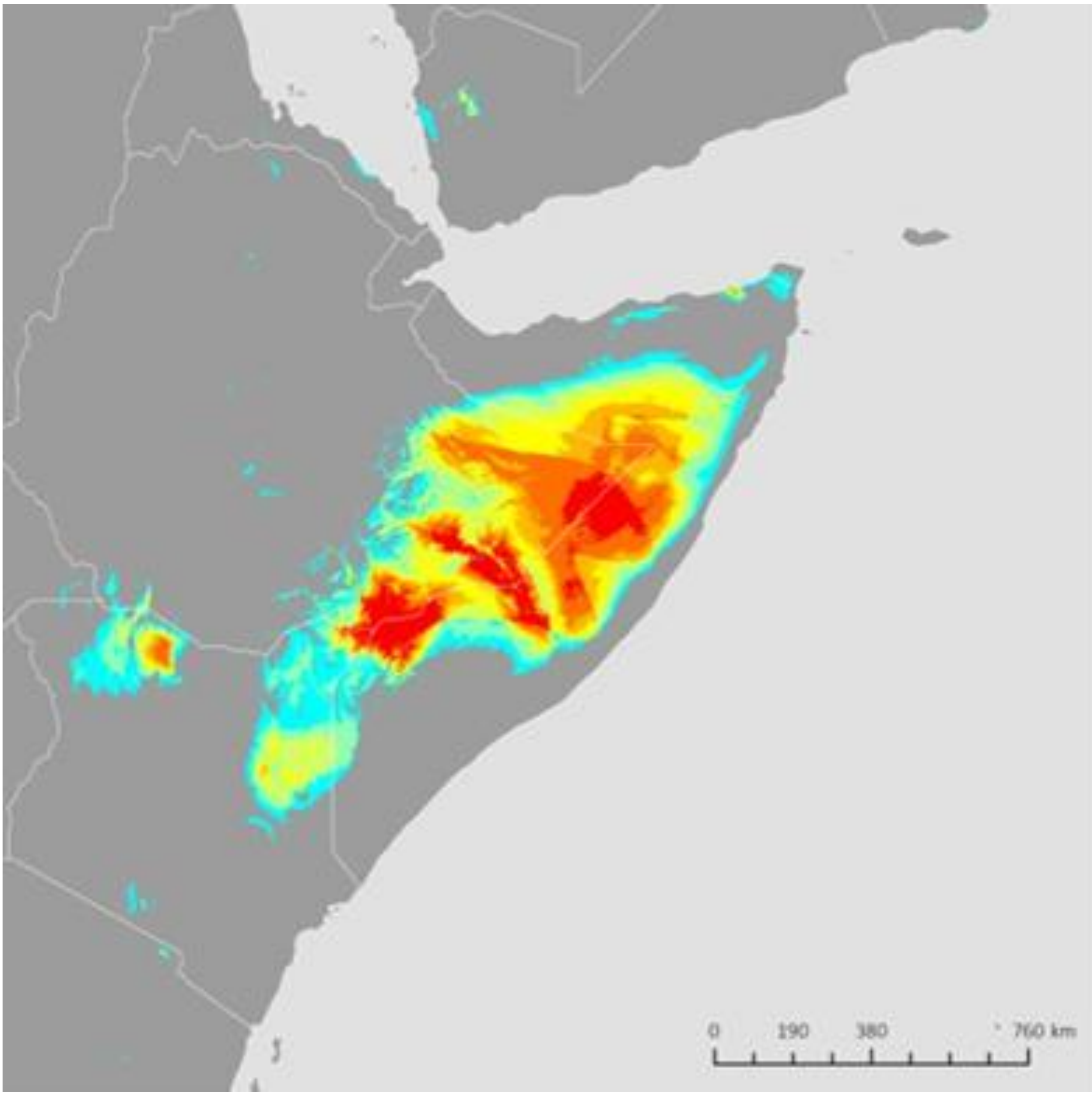

Figure 3.7. Modelled current distribution of *B. rivae.*

Boswellia sacra

This species was modelled using environmental data segregated by continent (Figure 3.8a, b & c). This revealed that much of the environmental niche in Arabia is also found within a small area of Somalia, whereas the opposite is less true. While this points to a potential dispersal from Somalia to Arabia, that is conjectural and requires formal testing, as do proposals suggesting that *B. sacra* in Arabia has its source in Somalia through transportation. Molecular studies showing significant variation within Oman argue against introduction as an explanatory factor.

A considerable amount of distribution data has been acquired for populations in Oman by another research group working under the auspices of the Environment Society of Oman, and it will be interesting to see how these records alter models and whether data is spatially biased due to sampling density.

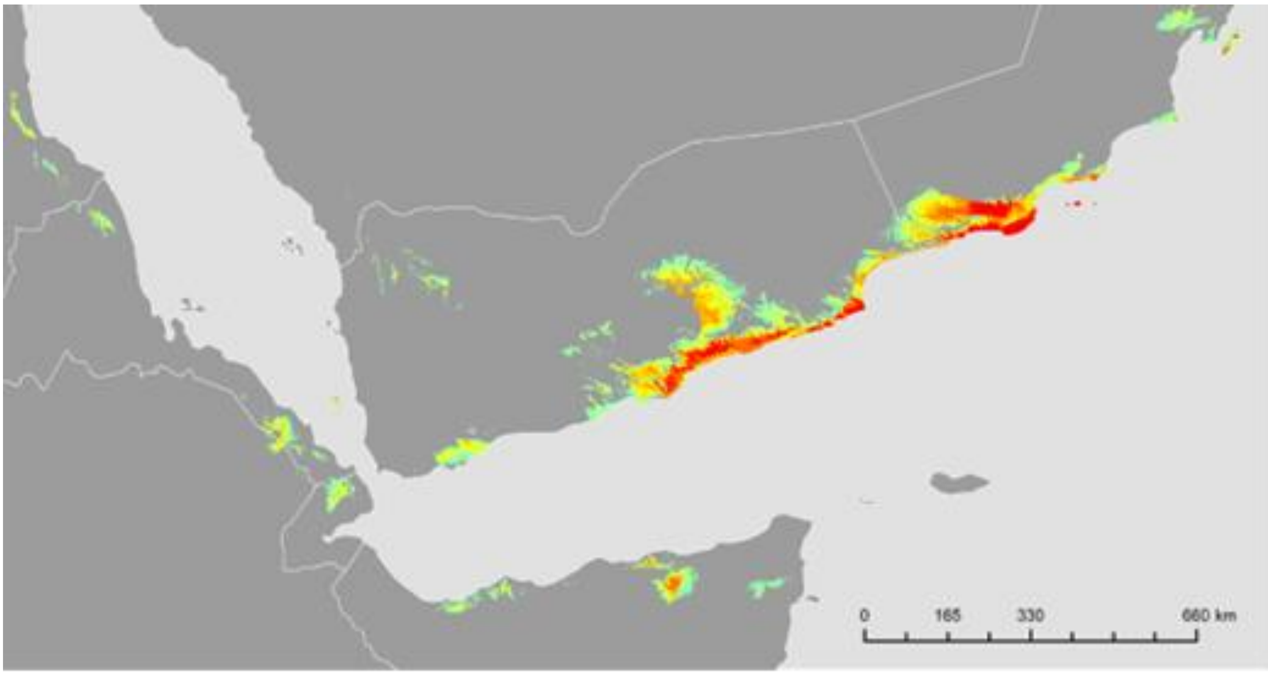

Figure 3.8a. Modelled current distribution of *B. sacra* using Arabian occurrence records only.

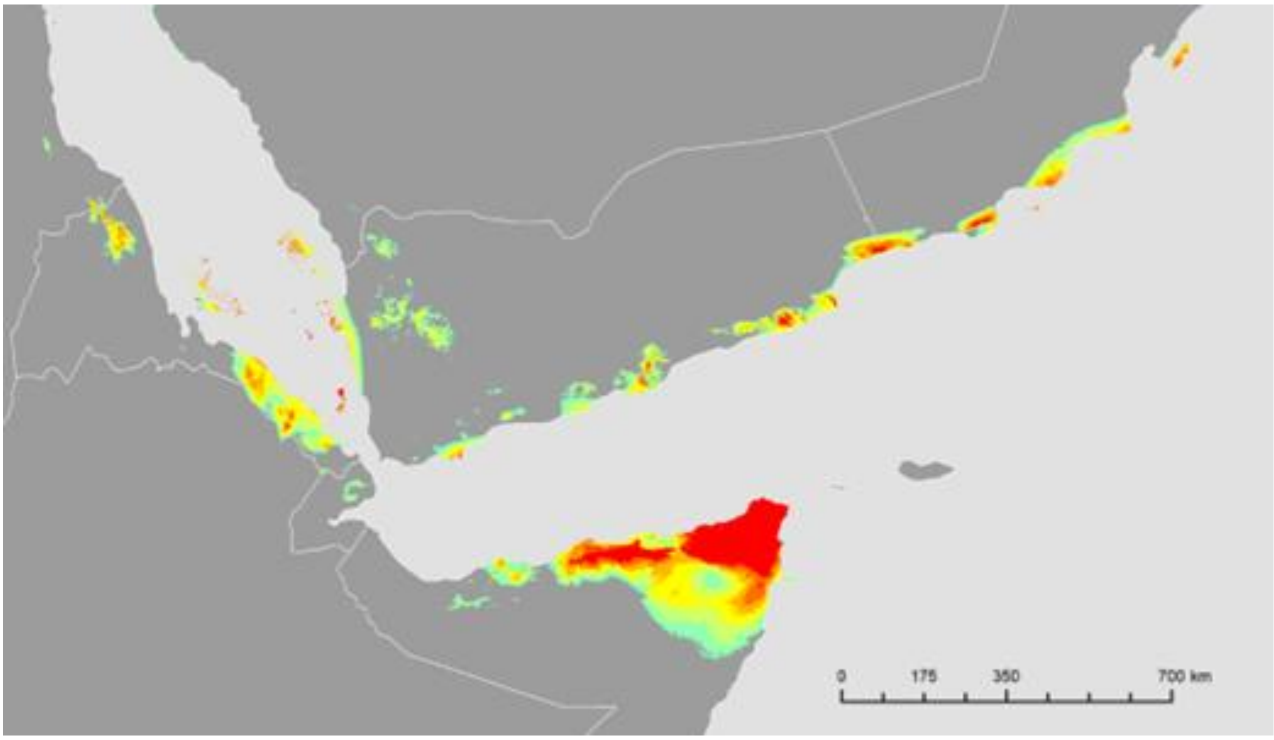

Figure 3.8b. Modelled current distribution of *B. sacra* using African occurrence records only.

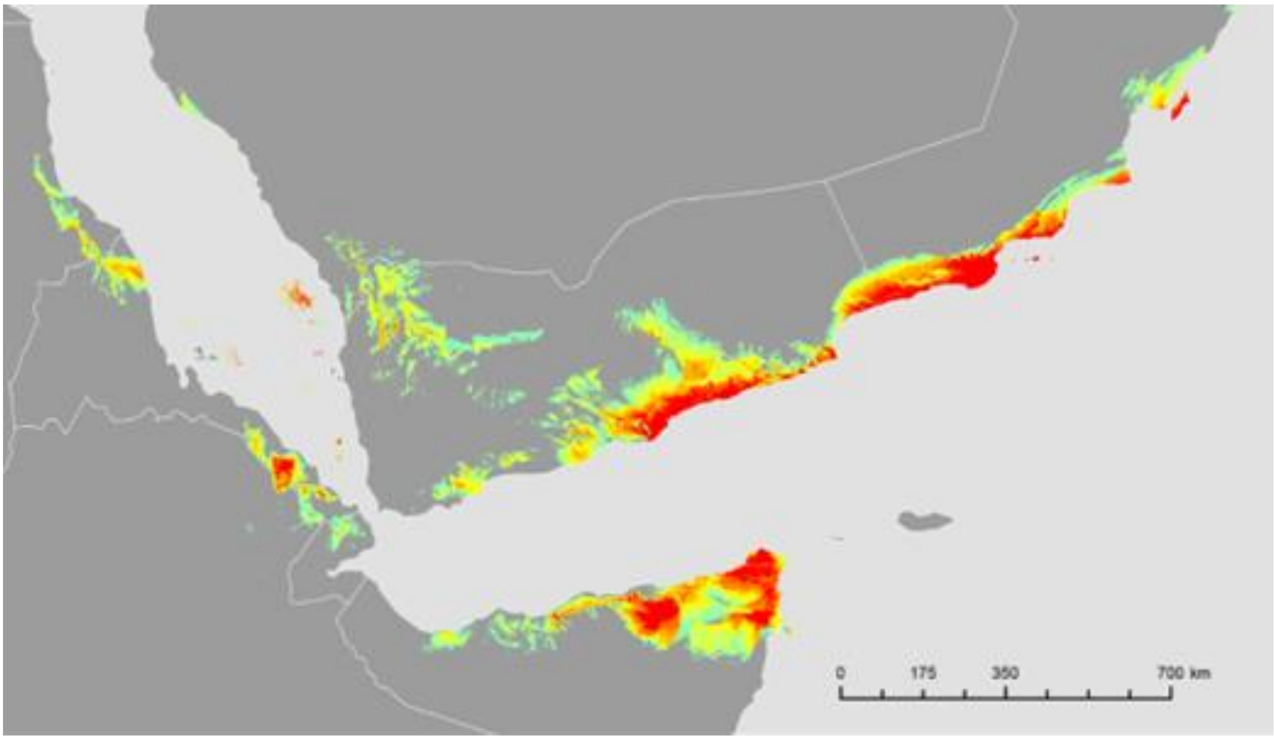

Figure 3.8c. Modelled current distribution of *B. sacra* using all occurrence records.

Boswellia serrata

Widespread and considered endemic to India, the model does not predict occurrences in neighbouring countries with high probability despite this being a widespread species (Figure 3.9.). The single historical occurrence in Sri Lanka is not predicted accurately. There is some conjecture about the provenance of that record. Recent reports of this species occurring in Pakistan and southeast Iran require verification and would likely alter model distributions.

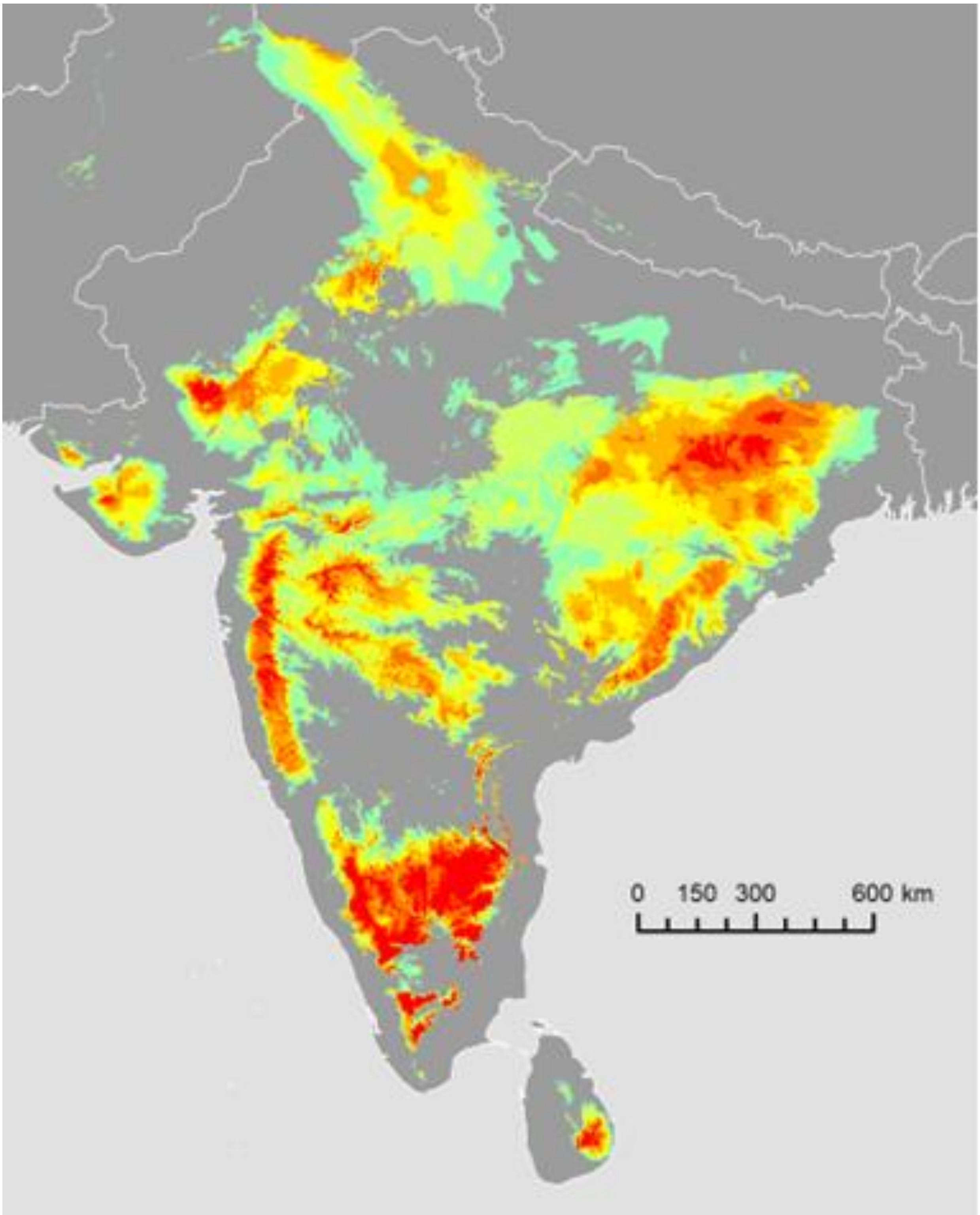

Figure 3.9. Modelled current distribution of *B. serrata*.

Discussion

SDM outputs always require careful interpretation. Whether or not a species will be found in an area that has a high probability value (i.e. suitable climatic conditions) depends on several factors, such as dispersal ability, biogeographic history, and species interactions. It is essential to take this information (if known) into consideration. Land use and land cover change should also be examined to determine whether suitable habitat has been lost or degraded due to agriculture or urbanisation. Site photographs from rapid field surveys suggest this may be an issue in several *Boswellia* range states, where at many locations, isolated *Boswellia* trees are surrounded by land cleared for crops. A full survey of modelled distributions against detailed satellite imagery to determine land use change over the last 40 years will require significant additional research time but will be invaluable to determine where *Boswellia* stands still occur in their natural state for conservation purposes.

These preliminary models only use climate data. Further investigation is required to understand what other environmental variables might be important in determining the distribution of these species. Edaphic factors such as soil type or geology could be useful, but it can be challenging to find suitable datasets that cover such a large area of interest and that are at an appropriate resolution (or that can be resampled without losing valuable information). Previous studies indicate that limiting the number of variables in a model reduces model complexity and therefore reduces overfitting (Fois et *al.,* 2015) so it may be beneficial to remove the less important climate variables if new environmental variables are being included in the model. For these models we used the same set of climate variables for all species to enable direct comparison among species. The analyses of variable contributions are informative and there are clearly similarities between some species. This information should be used to refine the models (i.e. use of different sets of variables for different species).

Modelling species distributions under future climate change scenarios has practical applications (in terms of understanding range shifts and/or potential habitat loss) but revision of existing models with a view to improving our understanding of current distribution is the first priority. This, together with an in-depth land use and land cover change study (e.g. time series analysis of remote sensing data) covering all nine species in this report (i.e. a large geographic area), and potentially testing some model results in the field, would require significant additional research time and resources. It would make a substantial contribution to informing the conservation and management of these culturally and economically valuable species.

Section 3.3

Conclusions

Significant effort has been made to increase the number and accessibility of vouchered and georeferenced specimens available for all species of *Boswellia*, more than doubling those referenced in Thulin (2020). This information is uploaded to the Frankincense Resource Portal and will shortly be available to researchers – to add more information, and to download for use in multiple assessments and analyses. Additional records have been acquired for field and literature records – also in the Portal – which add additional and secondary distribution information. There is little doubt that this resource will increase in the future.

Use of this data to model the distribution of species amenable to modelling has revealed some additional distribution trends and likely areas not previously considered to contain *Boswellia* species. The maps will better enable range States to target survey work. Several Stares have requested that we assess distribution against Protected Areas, and work is starting to ensure all relevant Protected Area information is available electronically for inclusion in this work.

Assessing distributions against future climate models requires model assessment and will be timetabled at RBGE.

Section 3.4

Outputs

Publications in open access peer-reviewed journal:

(a) Species Distribution Modelling of nine species of *Boswellia*

(b) Coverage of frankincense trees (*Boswellia* spp., Burseraceae) in Protected Area Systems globally

(c) How will frankincense be affected by the climate crisis?

Section 3.5

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