Modelling the Role of Multiple Global Change Drivers on Future Range Shifts in a Tropical Biodiversity Hotspot

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Summary

In a rapidly changing world, climate and land cover change are driving shifts in plant distributions globally. Predicting plant species ranges into the future is a conservation priority, especially in areas of high endemism and geographic isolation that exacerbate vulnerabilities to adaption. Moreover, plants like *Calophyllum* are experiencing high rates of mortality linked to a newly identified vascular wilt pathogen. We mapped the current distribution of *C. paniculatum* and its wilt, before predicting its range under multiple future climate and land cover scenarios. Our goal: to disentangle the multifaceted threats to plant species in a tropical Biodiversity Hotspot.

KEYWORDS: range shift, species distribution model, SDM, climate change, Tropics

Background

Our world is undergoing unprecedented global environmental change, and the importance of monitoring and protecting Biodiversity Hotspots (Myers et al., 2000) cannot be understated. At broad scales, anthropogenic climate change is expected to be a large driver of changes in biodiversity patterns (Kuhn et al., 2016). Uncertainties persist in how individual species may respond in tropical regions with more extreme climatic conditions (Rumpf et al., 2019). Additionally, the potential impact of increased habitat degradation—and in some cases, complete forest loss—due to future land use and land cover change on species' ability to disperse across local and regional scales remains an understudied risk.

Extinction risk is highest on geographically isolated islands with high endemism such as Madagascar. For plants like *Calophyllum paniculatum* (*C. paniculatum*), they face a triple threat: climate change, deforestation, and disease.

Study species & region

Calophyllum is a genus of evergreen tropical flowering plants in the order "Malpighiales". Botanists in Ranomafana National Park, Madagascar (**Figure 1**, **Figure 2**) believe this species is experiencing high adult mortality due to a wilt-pathogen, believed to be *Verticillium (Wright et al., 2020)* (**Figure 1**). Transportation of timber from nearby Mauritius and Seychelles where this wilt has been affecting other *Calophyllum* trees since the early 20th century may have facilitated the spread to Madagascar (Hill et al., 2003).

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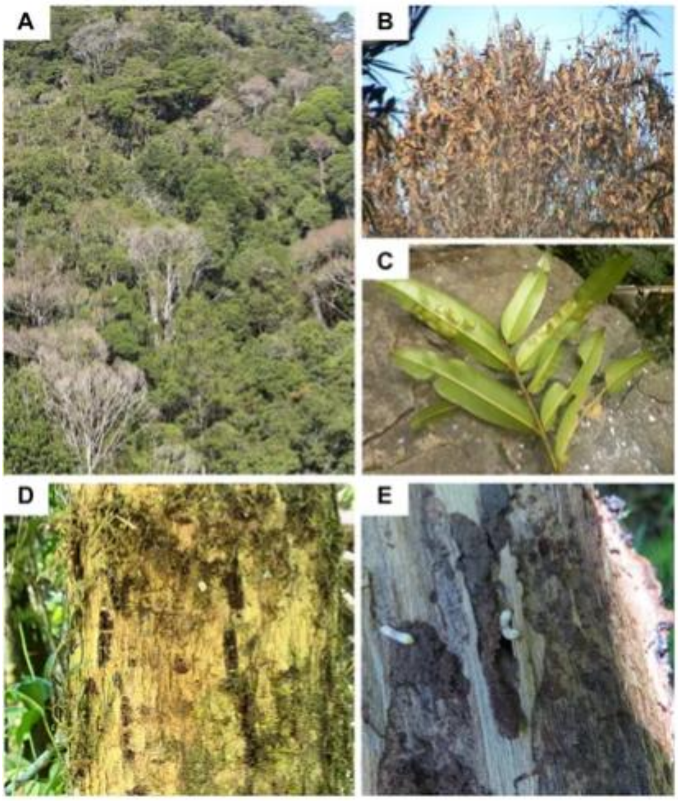


Figure 1 Note: "**Figure 2.** Photos of infected *Calophyllum* trees in Ranomafana National Park". Reprinted from Wright et al. (2020).

Madagascar (and the Indian Ocean Islands) is one of 36 globally designated Biodiversity Hotspots (**Figure 2**). Home to a high percentage of endemic species alongside high rates of habitat loss (Mittermeier et al., 2011). The evolution and endemism of trees like *C. paniculatum*, are attributed to isolation from its last connected land mass (Storey et al., 1995), and microclimatic conditions due to the size, location, and contrasting topography.

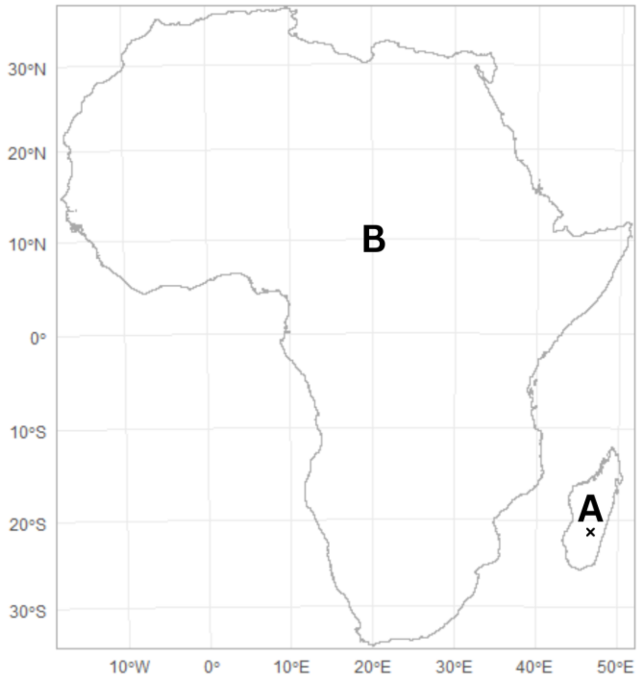


Figure 2 The two geographical extents for computing cSDMs on *Calophyllum*: extent A (Madagascar) and associated wilt pathogen *Verticillium* genera: extent B (African mainland). Ranomafana National Park is represented by a black cross in Madagascar.

Range shift definition

Understanding how species will respond to global and local change drivers is an important modelling concept within spatial ecology and conservation. One way to measure their adaptation through time is to calculate the difference between their current and predicted ranges in geographical and environmental space. Using established metrics such as those employed to produce the IUCN Red List, means model outputs can be converted to something more tangible, thus increasing their potential contribution to conservation outcomes (**Table 1**). We, therefore, define a range shift as a 'geographical change (latitudinal, longitudinal, or elevational) to an estimated species range across a measured time period' (Lenoir and Svenning, 2013).

Species distribution models

Correlative Species Distribution Models (cSDMs) are useful tools in ecology, biogeography, and conservation biology used to predict current and future species ranges, offering insights for conservation planning and climate change impact assessment (Elith and Leathwick, 2009). cSDMs correlate species occurrence data with environmental predictor variables to estimate the relationship between species and their environment (Franklin, 2010). cSDM workflows can be split into two main sections: data preparation and modelling. Preparation encompasses cleaning and processing of inputs, for example, cropping, bias corrections, and partitioning of occurrences into training and testing data (Kass et al., 2024). Modelling accounts for training and testing (via model performance) and producing predictions using the trained model and future versions of the environmental predictors.

Methods

We used an ensemble cSDM approach to model *C. paniculatum* under multiple future climate and land cover scenarios to 2100. We used three machine learning algorithms – Random Forests, Boosted Regression Trees and Maximum Entropy, replicating each ten times (Araújo and New, 2007, Hao et al., 2020). For species occurrences, we prepared data from Global Biodiversity Information Centre (GBIF). For predictor variables, we stacked CHELSA bioclimatic and 'forestatrisk' deforestation raster layers across current and future time periods and climate scenarios (Fick and Hijmans, 2017, Ghislain et al., 2023, Philipp et al., 2022). We used 5-fold cross validation with an 80:20 split for training and testing. Model performance was measured using Area under Curve (AUC), True Skill Statistic (TSS) metrics and their standard deviations to assess stability. *C. paniculatum* was trained, tested and predicted over Madagascar, and the wilt genera *Verticillium* was trained and tested over Africa, and transferred across Madagascar for predictions.

Continuous predictions were converted to binary presence-absence maps using threshold values to calculate potential range shifts and assess their overlap into the future. Standardised range shift metrics were computed using four approaches across multiple future climate pathways and year ranges (**Table 1)**.

Table 1 Standardised area-based range shift metrics, descriptions and reference to their use in other studies

Range shift metric	Description	References
Habitat distance	Median distance between the centroid of the current range and each predicted presence cell	(Choe et al., 2017, Radinger et al., 2017, Yesuf et al., 2021)
Habitat exposure	Difference between the current area range and the area of intersection between current and future range, divided by current range	
Spatial disruption	Subtract the area of the predicted future range from the current area range, divided by the total area of Madagascar	
Potential Area of Occupancy (pAOO)	Potential area of habitat occupied by a species using a standardised 2x2 grid	(IUCN Standards and Petitions Committee., 2022)

Results

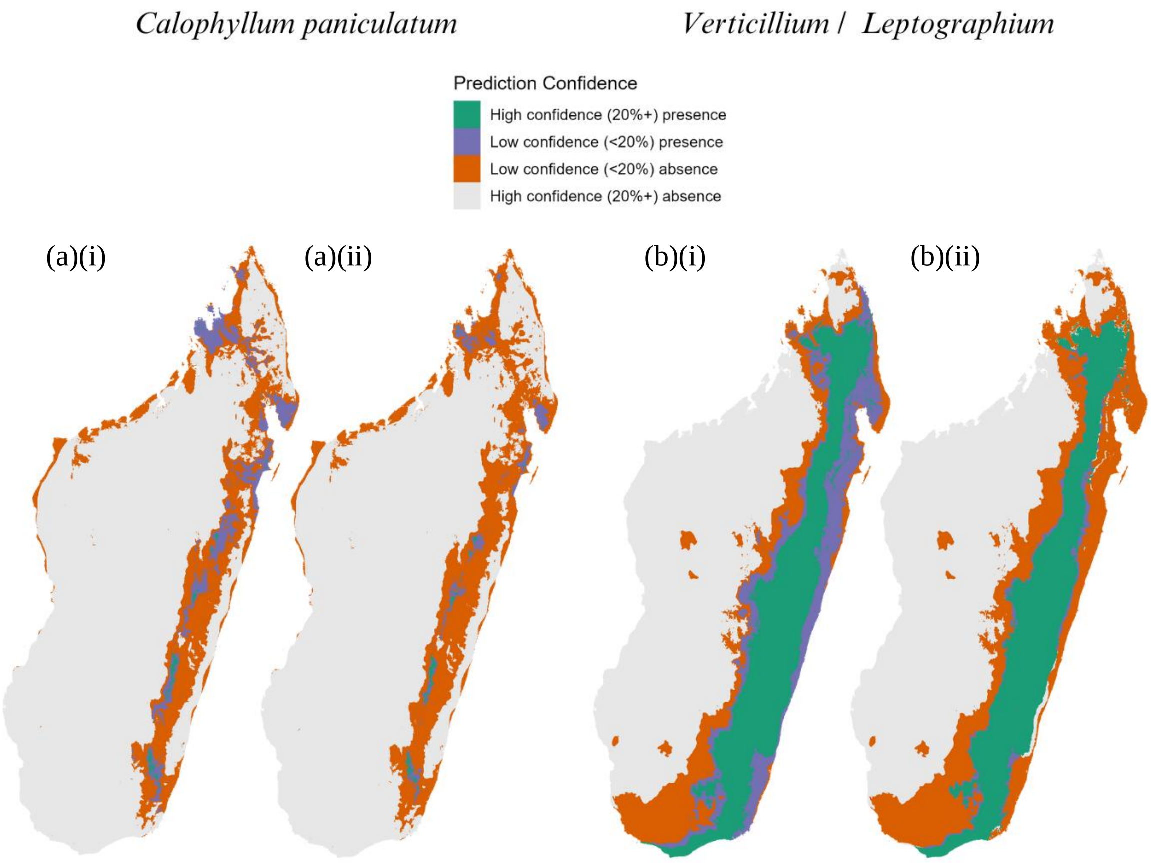
Initial performance indicators of the ensemble models suggest a very good fit for both species (**Table 2**). All models demonstrate high predictive power, with Area Under the Curve (AUC) values above 0.95.

Binary maps with uncertainty (**Figure 3**) show *Calophyllum* appears to be suitable across 3.6% of Madagascar, and *Verticillium*, 28.5%, with strong spatial overlap in high confidence presences in the north-south humid forest ecoregion.

Table 2 Summary of final environmental predictors and ensemble performance metrics: AUC, TSS and their standard deviation

cSDM ensemble	**Predictor variables***	**AUC**	**TSS**	**SD (AUC)**	**SD (TSS)**
C. paniculatum	Mean Temp Dry Q, Precip Wet Month, Ann Temp Range, Precip Cold Q, Temp Seasonality, Forest cover	0.982	0.933	0.016	0.040
Verticillium/ Leptographium	Precip Dry Month, Precip Seasonality, Mean Temp Cold Q, Precip Cold Q	0.950	0.864	0.035	0.080

***Full predictor names (Karger et al., 2017, Philipp et al., 2022): Mean Temperature of the Driest Quarter (BIO9), Precipitation of Wettest Month (BIO13), Annual Temperature Range (BIO7), Precipitation of the Coldest Quarter (BIO19), Temperature Seasonality (BIO4 – standard deviation x 100), Forest cover (binary), Precipitation of the Driest Month (BIO14), Precipitation Seasonality (BIO15), Temperature of the Coldest Quarter (BIO11).



Projection time period: 1981-2010		
Binary threshold	Opt 2 0.338	Opt 12 0.445
Uncertainty threshold (80th percentile)	0.211	0.211
Suitable habitat		
No. suitable cells	30334	12470
% suitable cells in total area	5.1%	2.1%
High confidence suitable habitat		
No. suitable cells	1925	1925
% high confidence cells in suitable area	6.3%	15.4%

Projection time period: 1981-2010		
Binary threshold	Opt 4 0.264	Opt 12 0.445
Uncertainty threshold (75th percentile)	0.784	0.784
Suitable habitat		
No. suitable cells	198712	138713
% suitable cells in total area	33.5%	23.4%
High confidence suitable habitat		
No. suitable cells	129468	125516
% high confidence cells in suitable area	65.2%	90.5%

Figure 3 Binary projections of high and low confidence presence (green/purple) and absence (grey/red) of *C. paniculatum* (a) and *Verticillium/Leptographium* (b) across Madagascar using current bioclimatic and forest cover predictors. Maps are split between two thresholds per species. 'Opt 2' (a)(i) weights thresholds based on models within each ensemble that maximise sensitivity and specificity (TSS), 'Opt 4' (b)(i) is based on the minimum distance to the Receiver Operating Curve (ROC) curve, and 'Opt 12' (a)(ii) & (b)(ii) is based on the10th percentile training presence.

Discussion

Preliminary results suggest that with current rates of pathogen caused mortality and future habitat suitability, sub-populations of *C. paniculatum* may not be sustainable without intervention or support. Localised change drivers such as fragmentation of forest edges, with the additional increased mortality due to the pathogen spread, may have more direct impacts on the plants' future status than climate. Further analysis is underway to ascertain the risk posed by localised environmental factors such as the pathogen spread within local population dynamics, to understand what this means for biodiversity in Madagascar.

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Biographies

PhD candidate Emma Underwood (corresponding author) – ELU
ELU graduated with a BSc in GIS from Newcastle University and spent 8 years in the GIS profession before moving back to academia to research the best ways to model future range shifts of plant species in response to climatic, land-use and land cover changes in Madagascar.

Associate Professor Kerry Brown (1st supervisor) – KAB
KAB is a plant ecologist and conservation biologist. He received a BSc in Biology from Howard University, MSc and PhD from Stony Brook University and a postdoctoral fellowship at Columbia. His research integrates ecological data at multiple spatial scales to assess how environmental change impacts on biodiversity patterns/ecosystem function.

Professor Nigel Walford (2nd supervisor) – NW
NW studied Geography before gaining a PhD (University of London) where he worked on rural change. His research reflects a longstanding focus on quantitative analysis of geospatial data in relation to geodemographics, spatial planning, and environmental monitoring. NW has been funded by ESRC, Scottish Executive, Nuffield and the British Academy.

Professor Mark Mulligan (3rd supervisor) – MM
MM's research interests include modelling land surface and ecological impacts of environmental change especially land-use change and climate change; desertification and land degradation in arid and semi-arid environments; hydrological processes and impacts in Mediterranean and tropical environments with particular emphasis on vegetation hydrology interactions; tropical forest processes and dynamics.