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Modeling the Spatial Distribution and Adaptive Conservation Strategies of *Pentachlaena latifolia* H. Perrier (Sarcolaenaceae) under Climate Change in the Ibity Massif Protected Harmonious Landscape

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Abstract: *Background: Pentachlaena latifolia H. Perrier (Sarcolaenaceae) is an endemic species of the Central Highlands of Madagascar, mainly found in the Tapia forests of the Ibity Massif. Its limited dispersal capacity makes it vulnerable to climate change. This study aims to model its future distribution to assess habitat dynamics and guide adaptive conservation.*

Materials and Methods: Occurrence data obtained from GBIF, Tropicos, the PBZT herbarium–COST 01, and field surveys were spatially filtered at a resolution of 1 km × 1 km and analyzed using the Biomod2 platform in R through an Ensemble Modelling approach (GLM, GAM, RF, MaxEnt, and GBM). Current and future projections (2041–2060) were generated using seven bioclimatic variables from WorldClim v2.1 under the SSP2-4.5 and SSP5-8.5 climate scenarios.

Results: The model showed excellent predictive performance (AUC = ; TSS =). Species distribution was mainly influenced by precipitation seasonality (BIO15:) and precipitation of the driest month (BIO14:). Projections indicate a shift in suitable habitats toward high-altitude ridges (800–1,000 m), accompanied by a net habitat loss of under the SSP2-4.5 scenario and under the SSP5-8.5 scenario. Only of the potential climatic refugia are currently covered by the Ibity Massif Protected Area, while the existing Management and Development Plan (PAG) does not explicitly incorporate climate change.

Conclusion: Climate change represents a major threat to P. latifolia. Its conservation requires adaptive management based on the expansion of protected areas toward high-altitude climatic refugia, restoration of Tapia forests, strengthening of ecological connectivity, in situ and ex situ conservation, and dynamic revision of managements plans.

Keywords: Pentachlaena latifolia; climate change ; Species distribution ; Biomod2 ; conservation ; climatic refugia.

I. INTRODUCTION

The genus *Pentachlaena*, described by Henri Perrier de la Bâthie during his studies of the flora of Madagascar, belongs to the endemic family Sarcolaenaceae (Perrier de la Bâthie, 1920; Schatz, 2001; Andriamihajarivo et al., 2016). Among the species of this genus, *Pentachlaena latifolia* H. Perrier is a tree or shrub endemic to the Central Highlands of

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Madagascar (Missouri Botanical Garden Madagascar, 2020). The species is mainly distributed on quartzitic outcrops of the Ibity Massif and adjacent areas of the Central Plateau, where it is associated with Tapia (*Uapaca bojeri*) open woodlands (Lowry II et al., 2000; Schatz, 2001). It has important ecological and socio-economic value within these ecosystems. Morphologically, *P. latifolia* differs from *P. vestita* by its larger leaves, a higher number of secondary veins, and less dense pubescence on the branches, petioles, and abaxial surface of the leaves, which constitute key diagnostic characters for species identification (Schatz, 2001).

Climate change is currently one of the major threats to the conservation of endemic plant species, progressively altering the bioclimatic conditions that determine their distribution and long-term persistence (Chen et al., 2011; Dobrowski et al., 2021). Owing to its sessile nature and limited dispersal capacity, *P. latifolia* is particularly vulnerable to changes in its habitat, especially shifts in precipitation regimes, which strongly influence its ecological niche (Heller & Zavaleta, 2009; Mauri et al., 2023). Under these changing conditions, protected-area networks based on fixed geographical boundaries may no longer provide effective protection for future suitable habitats, highlighting the need for a more dynamic and forward-looking conservation approach (Dobrowski et al., 2021; Heller & Zavaleta, 2009).

In this context, Species Distribution Modelling (SDM) provides a relevant tool for anticipating the effects of climate change, identifying potential climatic refugia, and guiding conservation strategies. The present study uses an Ensemble Modelling approach implemented in the Biomod2 platform to model the current and future distribution of *P. latifolia* for the period 2041–2060 under the SSP2-4.5 and SSP5-8.5 climate scenarios, assess potential habitat changes, and identify adaptive conservation priorities to strengthen the protection of this endemic species within the Ibity Massif Protected Harmonious Landscape.

II. MATERIALS AND METHODS

2.1. Occurrence Data and Environmental Variables

Occurrence data for *Pentachlaena latifolia* H. Perrier were compiled from the GBIF databases (Alvarado et al., 2015; Missouri Botanical Garden, 2018; Andriamihajarivo et al., 2016) and Tropicos (Missouri Botanical Garden, 2026), herbarium specimens preserved at the Tsimbazaza Botanical and Zoological Park (PBZT-COST-01) (Ramanandraisoa & Rakotomanjaka, 2016), as well as field surveys conducted within the known distribution range of the species. A total of 78 occurrence records were compiled. Following spatial filtering to reduce sampling bias, with only one occurrence retained per 1 km × 1 km grid cell, 35 unique occurrences were retained for modeling (Figure 1).

Table 1. Sources of occurrence data for *Pentachlaena latifolia* used in the modeling.

Source	Number of occurrences
GBIF	20
Tropicos	15
PBZT	8
Field surveys	35
Total	**78**

When multiple occurrence records fell within the same grid cell, the record obtained from field surveys conducted as part of the present study was preferentially retained. Environmental variables were extracted from the WorldClim version 2.1 database at a spatial resolution of 30 arc-seconds (approximately 1 km²) (Missouri Botanical Garden, 2018).

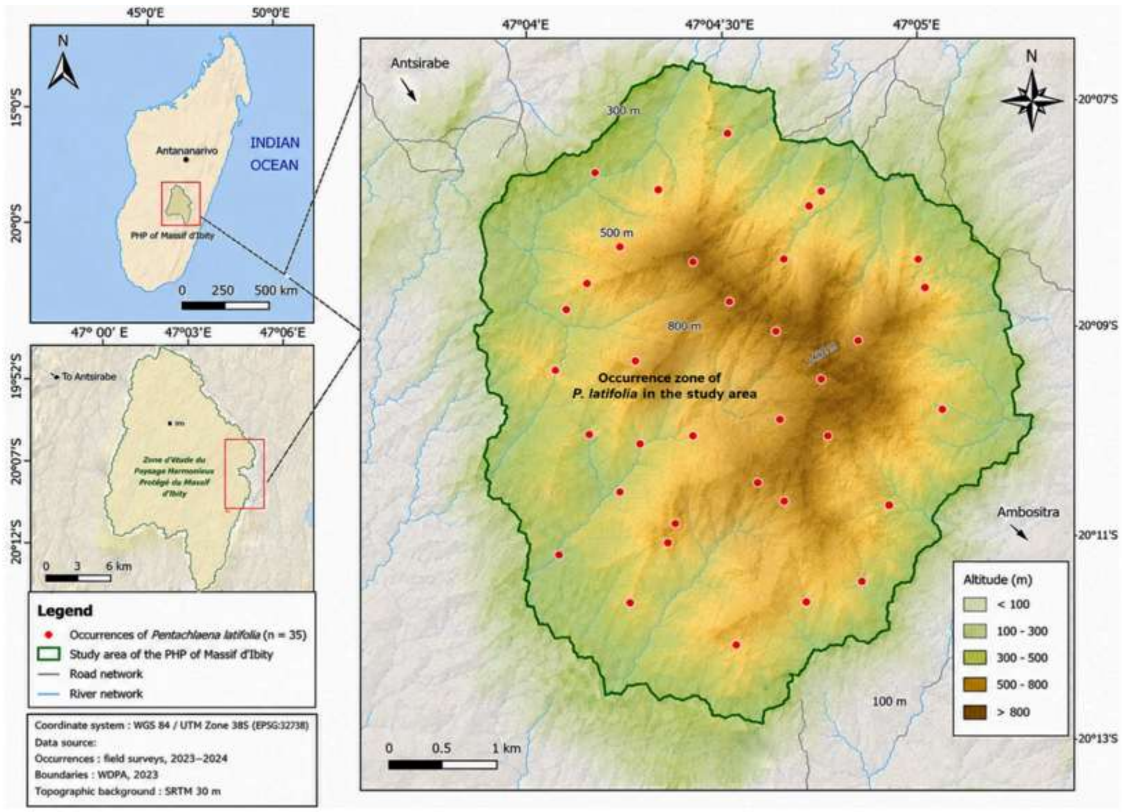

Figure 1. Location of the 35 occurrences of *Pentachlaena latifolia* within the study area of the Ibity Massif Protected Harmonious Landscape.

2.2. Spatial Distribution Modeling

The potential distribution of *Pentachlaena latifolia* H. Perrier was modeled in R using the BIOMOD2 platform through an Ensemble Modeling approach combining five complementary algorithms: Generalized Linear Model (GLM), Generalized Additive Model (GAM), Random Forest (RF), Maximum Entropy (MaxEnt), and Generalized Boosted Models (GBM). This approach accounts for uncertainty associated with algorithm selection and provides more robust predictions (Thuiller et al., 2009).

Seven bioclimatic variables derived from WorldClim version 2.1 (BIO1, BIO7, BIO12, BIO14, BIO15, BIO18, and BIO19) were selected for the modeling procedure (Fick & Hijmans, 2017).

To minimize the effects of multicollinearity, a Pearson correlation analysis was performed across the geographical extent of the study area. Only variables with correlation coefficients below the predefined threshold ($|r| \leq 0{,}75$) and considered biologically relevant to *P. latifolia* were retained in the final model (Table 2).

The models were developed using the available presence data, together with absence or pseudo-absence data generated when required by the modeling algorithms. A k-fold cross-validation strategy was implemented using five folds and three repetitions to assess model robustness. Models were trained using 80% of the data and evaluated using the remaining 20%.

The relative importance of the bioclimatic variables was estimated using permutation tests. Model predictive performance was assessed using the Area Under the Curve (AUC) and the True Skill Statistic (TSS). TSS is widely used to evaluate the performance of species distribution models (Allouche et al., 2006). Only models with a TSS > 0.70 were retained for the final ensemble. The selected models were subsequently combined into an Ensemble Model to generate a consensus estimate of the current and future potential distribution of the species (Thuiller et al., 2009).

Table 2. Bioclimatic variables selected for modeling the distribution of *Pentachlaena latifolia*

Bioclimatic variable	Abbreviation
Annual Mean Temperature	BIO1
Annual Temperature Range	BIO7
Annual Precipitation	BIO12
Precipitation of Driest Month	BIO14
Precipitation Seasonality	BIO15
Precipitation of Warmest Quarter	BIO18
Precipitation of Coldest Quarter	BIO19

2.3. Analysis of Habitat Dynamics and Conservation

Current and future distribution maps were binarized using the threshold that maximized the TSS (Allouche et al., 2006), and subsequently compared using QGIS and R to quantify habitat losses (Loss), habitat gains (Gain), and stable areas (Range Retention), which were considered potential climatic refugia. Net habitat change was calculated as the difference between habitat gain and habitat loss:

Net habitat change (%) was calculated as follows:

$$\text{Net habitat change }(\%) = \frac{\text{Future habitat area} - \text{Current habitat area}}{\text{Current habitat area}} \times 100$$

The effectiveness of the Madagascar Protected Area System (SAPM) was subsequently assessed by overlaying the identified climatic refugia with the boundaries of protected areas. This approach makes it possible to identify areas likely to remain suitable for the species under future climatic conditions and to guide conservation priorities (Thuiller et al., 2009; Heller & Zavaleta, 2009). Finally, a documentary analysis of the Management and Development Plans (Plans d'Aménagement et de Gestion, PAG) was conducted to assess the extent to which climate change is incorporated into current management frameworks and to inform recommendations for adaptive conservation.

The coverage of climatic refugia by the Ibity Massif Protected Area was assessed through spatial overlay of the projected refugia and the protected-area boundaries in QGIS. The proportion of refugia covered was calculated using the following formula:

$$\text{Coverage }(\%) = \frac{\text{Area of refugia within the protected area}}{\text{Total refugia area within the study area}} \times 100$$

The area of refugia located within the protected area was 250 ha, out of a total refugia area of 625 ha, corresponding to a 40% coverage.

III. RESULTS

3.1. Model Performance and Bioclimatic Variables

The Ensemble Modeling approach showed excellent predictive performance, with a mean AUC value of 0.89 ± 0.03 and a mean TSS value of 0.76 ± 0.04. Variable importance analysis indicated that the potential distribution of *Pentachlaena latifolia* was primarily influenced by precipitation seasonality (BIO15; 42.5%) and precipitation of the driest month (BIO14; 28.3%).

Table 3. Bioclimatic variables selected for modeling the distribution of *Pentachlaena latifolia*

Bioclimatic variable	Abbreviation	Relative importance (%)
Precipitation Seasonality	BIO15	42.5
Precipitation of Driest Month	BIO14	28.3

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Annual Temperature Range	BIO7	10.2
Annual Mean Temperature	BIO1	7.0
Annual Precipitation	BIO12	5.1
Precipitation of Warmest Quarter	BIO18	4.2
Precipitation of Coldest Quarter	BIO19	2.7
Total		**100.0**

3.2. Spatial Dynamics of Potential Habitat

Climate projections for 2041–2060 indicate a concentration of suitable habitats in high-altitude areas, particularly around 800–1,000 m, accompanied by an almost complete disappearance of suitable habitat at elevations below 500 m. Under the SSP2-4.5 scenario, 52.4% of the potential habitat remains stable, while 47.6% becomes unsuitable, with a potential habitat gain of 8.1%, corresponding to a net change of −39.5%. Under the SSP5-8.5 scenario, the proportion of stable habitat decreases to 31.2%, while habitat losses reach 68.8%, with a limited gain of 3.5%, resulting in a net change of −65.3%.

Table 4. Projection of potential habitat dynamics for *Pentachlaena latifolia* for 2041–2060.

Climate scenario	Stable area / Refuge (%)	Habitat loss (%)	Habitat gain (%)	Net change (%)
SSP2-4.5	52.4	47.6	+8.1	−39.5
SSP5-8.5	31.2	68.8	+3.5	−65.3

Under the SSP2-4.5 scenario, 52.4% of the potential habitat remains stable, whereas 47.6% is lost. Habitat gain is limited to 8.1%, resulting in a net habitat change of −39.5%.

Under SSP5-8.5, the situation is more critical: stable areas decrease to 31.2%, habitat losses reach 68.8%, and habitat gain is only 3.5%, resulting in a net change of −65.3%.

Thus, the SSP5-8.5 scenario results in a 21.2 percentage-point reduction in stable areas and a substantially greater net habitat loss. These findings indicate a high vulnerability of *P. latifolia* to climate change and highlight the need to strengthen adaptive conservation strategies.

Current distribution

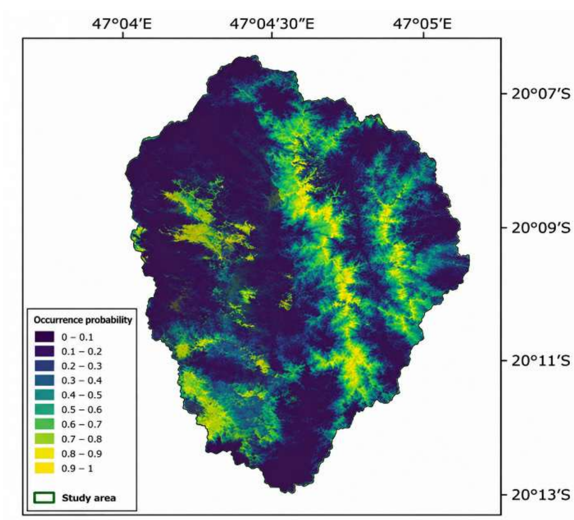

Figure 2: Current distribution of *P. latifolia*

The current distribution of *P. latifolia* shows areas of high occurrence probability mainly concentrated in the central and southern sectors of the study area, with lower values toward the peripheral areas. This distribution is therefore relatively concentrated in sectors characterized by environmental conditions that are most favorable to the species.

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Future distribution – SSP2-4.5 (2041–2060)

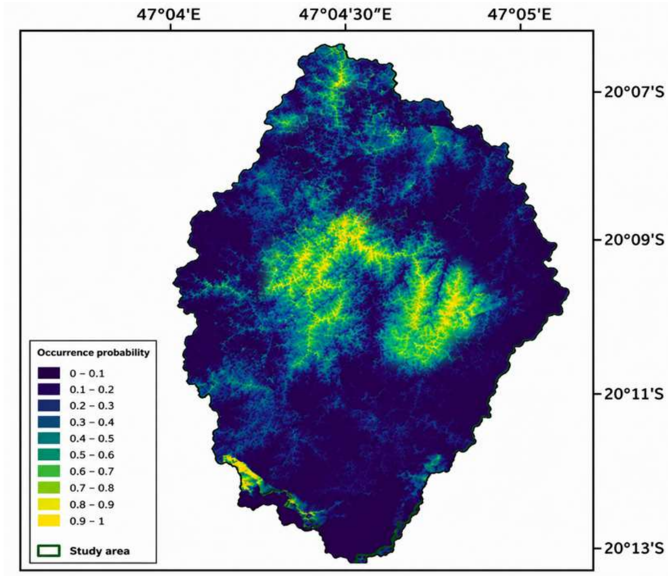

Figure 3: Future distribution – SSP2-4.5 (2041–2060)

Under the SSP2-4.5 scenario, areas with a high occurrence probability remain mainly concentrated in the central and eastern sectors of the study area, along high-elevation ridges. In contrast, occurrence probabilities become low across most lower slopes and peripheral areas. The favorable distribution therefore appears more restricted and fragmented compared with current conditions, indicating a reduction in the potential habitat of *P. latifolia*.

Future distribution – SSP5-8.5 (2041–2060)

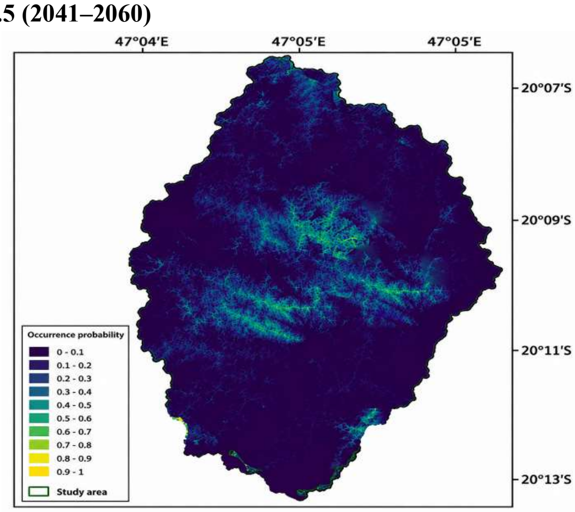

Figure 4: Future distribution – SSP2-8.5 (2041–2060)

Under the extreme SSP5-8.5 scenario (2041–2060), the degradation of bioclimatic suitability reaches a critical level (Figure 3). A generalized collapse in occurrence probabilities is observed across almost the entire study area (represented in dark purple). Only a few relictual refugia persist along the highest-elevation ridges in the central part of the area, where occurrence probabilities rarely exceed to. These results confirm a strong spatial contraction and a severe threat of local extinction for *P. latifolia* under the most unfavorable climate scenario.

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Table 5. Occurrence probability of *Pentachlaena latifolia* according to altitude under current conditions and future climate scenarios

Altitude	Current	SSP2-4.5 (2041–2060)	SSP5-8.5 (2041–2060)
1,000 m	0.92	0.55	0.25
800 m	0.88	0.35	0.10
500 m	0.65	0.15	0.02
300 m	0.15	0.02	0.00
100 m	0.08	0.00	0.00

The analysis of occurrence probabilities along the altitudinal gradient indicates a severe impact of climate change by 2041–2060. Under current conditions, higher elevations (800–1,000 m) exhibit highly favorable conditions, with occurrence probabilities ranging from 0.88 to 0.92. However, under future climate scenarios, a marked and generalized decline in occurrence probability is projected across all elevations. At 1,000 m, the probability decreases to 0.55 under the SSP2-4.5 scenario and declines sharply to 0.25 under SSP5-8.5. At elevations below 500 m, bioclimatic suitability becomes nearly negligible (≤0.02), confirming a high risk of local extinction of *P. latifolia* across its entire altitudinal range.

3.3. Coverage of the SAPM Network and Conservation Priorities

Spatial analysis indicates that 40% of the projected climate refugia under the SSP5-8.5 scenario are currently included within the Ibity Massif Protected Area, whereas 60% remain outside the protected area. Furthermore, a review of the available documentation, particularly the Management and Development Plan (Plan d'Aménagement et de Gestion, PAG) of the Ibity Massif, indicates that climate change is not explicitly incorporated into the current management framework.

The main conservation priorities identified include extending the protected-area network to encompass potential climate refugia, restoring Tapia forests, strengthening ecological connectivity, developing ex situ conservation measures, including seed banks and assisted migration, and implementing long-term monitoring of the species.

Table 6. Main conservation priorities proposed for *Pentachlaena latifolia*.

Strategic axis	Conservation priorities
SAPM expansion	Creation of new protected areas encompassing high-elevation climate refugia.
Ecological restoration	Restoration of Tapia forests (*Uapaca bojeri*) and sustainable management of bushfires.
Ecological connectivity	Establishment of ecological corridors and buffer zones between suitable habitats.
Ex situ conservation	Seed collection, establishment of germplasm banks, translocation, and assisted migration toward refuge areas.
Monitoring and governance	Periodic revision of the Management and Development Plan (PAG), long-term monitoring using remote sensing and GIS, and integration of local communities.

IV. DISCUSSION

4.1. Vulnerability of *Pentachlaena latifolia* to Climate Change

Distribution projections indicate a substantial reduction in the potential habitat of *Pentachlaena latifolia*, with a net change of −39.5% under the SSP2-4.5 scenario and −65.3% under the SSP5-8.5 scenario. These results confirm the high sensitivity of the species to changes in bioclimatic conditions, particularly those related to precipitation seasonality (BIO15) and precipitation of the driest quarter (BIO14). They are consistent with previous studies showing that climate change can substantially alter the distribution of plant species (Chen et al., 2011; Dobrowski et al., 2021; Heller & Zavaleta, 2009).

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The decline in occurrence probabilities at lower elevations and their relative persistence in higher-elevation areas, particularly between 800 and 1,000 m within the study area, suggest a future concentration of suitable habitats in these sectors. However, these projections are based on the assumptions inherent to species distribution models (SDMs), which do not necessarily account for phenotypic plasticity, biotic interactions, or certain geographic barriers. The resulting maps should therefore be considered decision-support tools rather than absolute predictions.

4.2. Implications for the Conservation of the Species

The spatial analysis highlights a mismatch between the potential climate refugia of *P. latifolia* and the current coverage of the Ibity Massif Protected Area. Indeed, only 40% of the identified climate refugia are currently included within the protected area, whereas 60% remain outside its boundaries. Furthermore, an analysis of the Management and Development Plan (Plan d'Aménagement et de Gestion, PAG) of the Ibity Massif indicates that climate change is not explicitly incorporated into the current management framework. These findings suggest that existing conservation measures may be insufficient to ensure the long-term protection of this endemic species.

The literature reviewed indicates that existing protected areas, which are generally based on static boundaries, may become inadequate as climate niches shift. This scientific evidence supports the adaptive conservation recommendations proposed in this study, particularly the expansion of protected areas, the strengthening of ecological connectivity, and the integration of climate change considerations into Management and Development Plans (PAGs).

In light of these findings, an adaptive conservation strategy appears necessary. Such a strategy should be based on extending the protected-area network toward potential climate refugia, prioritizing the protection of high-elevation habitats, restoring ecological connectivity within Tapia forests, and strengthening both in situ and ex situ conservation measures, particularly through the establishment of seed banks and the assessment of assisted migration programs. Integrating climate scenarios into future Management and Development Plans should also be considered a priority in order to enhance the resilience of *Pentachlaena latifolia* to environmental change.

The current Ibity PAG contributes to protecting the massif from direct anthropogenic pressures such as fires and mining activities (Missouri Botanical Garden [MBG], 2015). However, given the substantial reduction in suitable habitats predicted by our models under the SSP2-4.5 and SSP5-8.5 scenarios, revision of the PAG appears necessary, particularly in a context where gaps in climate-change adaptation also affect the national protected-area network (WWF & SAPM, 2021). Dynamic adaptation strategies should therefore be incorporated, including the maintenance or restoration of elevational ecological corridors to reduce population isolation under increasing temperatures (Trew & Maclean, 2021; Stephenson et al., 2020), as well as the identification and protection of climate refugia beyond the current boundaries of the Protected Area (Morelli et al., 2020; Diallo et al., 2023).

Based on the results obtained, several adaptive conservation measures can be proposed to strengthen the protection of *Pentachlaena latifolia*. These include extending the protected-area network toward potential climate refugia and prioritizing the protection of habitats likely to retain suitable environmental conditions for the species (Heller & Zavaleta, 2009; Morelli et al., 2020). Habitat restoration and the maintenance of ecological connectivity could also facilitate population movements in response to climate change (Hodgson et al., 2009; Raxworthy et al., 2008). The feasibility of assisted migration could be assessed, particularly through seed collection and the production of seedlings for future suitable habitats, while taking into account the ecological risks associated with this approach (Hoegh-Guldberg et al., 2008). Complementary in situ and ex situ conservation measures could also help reduce the risk of genetic diversity loss. Finally, the explicit integration of climate change into future Management and Development Plans (PAGs), together with regular ecological monitoring of populations, appears essential to strengthen the adaptive capacity of the species (Raxworthy et al., 2008; Heller & Zavaleta, 2009).

V. CONCLUSION

This study highlights the high vulnerability of *Pentachlaena latifolia* H. Perrier to climate change in the Central Highlands of Madagascar. Climate projections for 2041–2060 reveal a drastic contraction of its potential habitat, reaching

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a net loss of 65.3% under the most pessimistic scenario (SSP5-8.5), together with a shift in suitable bioclimatic conditions toward higher-elevation ridges.

Furthermore, the spatial analysis shows that 60% of the identified climate refugia remain outside the current network of the Madagascar Protected Area System (SAPM), while the current Management and Development Plan (PAG) does not explicitly incorporate climate change dynamics.

These findings highlight the urgent need to adopt an adaptive and dynamic conservation strategy. Targeted expansion of the protected-area network toward high-elevation refugia, restoration of Tapia forests, strengthening of ecological connectivity, and development of complementary **in situ** and **ex situ** conservation measures, including seed banks and assisted migration, represent key priorities for ensuring the long-term persistence of *Pentachlaena latifolia*.

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