



Vulnerability of lowland and upland orchids in their spatially response to climate change and land cover change

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ABSTRACT

Climate change and land cover change often interactively affect plant species distributions. This study addresses the vulnerability of lowland and upland orchids to climate change and land cover change. Endemic orchids of New Guinea were grouped into four classes (lowland epiphyte, lowland terrestrial, upland epiphyte, upland terrestrial) based on their life form and elevation range. Forty occurrence records of endemic orchids were selected for each class, totaling 160 occurrence records. Ensemble modelling combining two machine learning algorithms was used to generate predictive current and future suitable areas for orchid classes. Model performance was evaluated using the AUC and TSS metrics. Suitable areas for both lowland and upland orchids (epiphyte and terrestrial) were predicted decrease in the future due to climate change and land cover change. The loss of suitable areas for upland terrestrial orchids was predicted to be most significant in the worst-case climate change scenario (SSP 5–8.5). Both lowland and upland orchids (epiphyte and terrestrial) tend to shift to higher elevation ranges from the present distributions. The predictive models have AUC values >0.90 and TSS value >0.80, indicating the models have excellent potential for predicting the impact of climate change and land cover change on orchid distributions.

1. Introduction

Anthropogenic global change affects biodiversity across multiple spatial scales (Sax and Gaines, 2003). Climate change influences biodiversity loss, disrupts ecosystem functioning, and alters landscapes (Mooney et al., 2009; Sage, 2023). Climate and land cover changes are

major contributors to compositional shifts in tropical ecosystems. The degradation and conversion of forests to alternative land uses, such as agriculture, is one of the leading causes of biodiversity loss, especially in the tropics. A number of studies has been conducted to integrate land-cover and bioclimate data to predict impacts on biodiversity (Brown et al., 2015; Evans et al., 2020; Pearson et al., 2004). A combination of

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climate and land cover change has influenced plant diversity across Madagascar through the alterations of potential habitat (Brown et al., 2015).

The Orchidaceae is one of the largest flowering plant families with >28,000 species within 763 genera (Christenhusz and Byng, 2016; Gale et al., 2018). This family contains a large number of rare species (Kirillova et al., 2023). Many orchids are rare because they are restricted to small geographic extents (Waterman and Bidartondo Waterman and Bidartondo, 2008). Orchids are widely used for ornamental and medicinal purposes (Zhang Zhang et al., 2018). Orchid ecology can be complex and often unique, based on life histories, growth forms and a wide variety of habitats (Zhang et al., 2018). Orchid life forms include epiphyte and terrestrial types (Sosa et al., 2016). Epiphytic orchid comprises 19,000 species, a number greater than that of terrestrial orchid species (Zotz and Winkler, 2013). Epiphytic orchids often live in tree canopies and stems with modified roots with a surficial velamen structure. The roots sometimes grow >1 m long. The velamen structure functions to absorb moisture and nutrients from the surrounding atmosphere (Zhang et al., 2018; Zotz and Winkler, 2013). In addition, the epiphyte orchids develop anatomical and physiological traits that enhance water storage and reduce water loss (Zhang et al., 2018). Terrestrial orchids have a thick and fleshy structure that grows downward into the soil. Epiphyte orchids tend to have thick, succulent leaves, thick cell walls, and smaller stomata compare to terrestrial orchids (Guan, 2011; Sailo and Rai, 2019; Zhang et al., 2018).

New Guinea has a remarkably diverse flora including orchids, with a level of endemism that is considerably higher than that of other Southeast Asian islands (Roos et al., 2004; Van Welzen, 1997). The island is also known to harbor one of the richest orchid floras (Orchidaceae) in the world (Schuiteman and De Vogel, 2007). New Guinea has 2856 species of orchids and about 95% of them are endemics (Schuiteman et al., 2010). Studies on orchid diversity in New Guinea are limited, since the island is still comparatively under-collected (Mittermeier et al., 1998). Orchids in New Guinea have the highest levels of

species richness in the central mountain ranges of the east, including part of the Papuan Peninsula (Vollering and Raes, 2016). This pattern is similar to that found in mountainous regions of Costa Rica (Crain et al., 2020).

Orchids are very sensitive to environmental change either directly, or indirectly through interactions with their host trees (Swarts and Dixon, 2009). The sensitivity of orchids to changing environments, makes them good indicators of ecological status (Gale et al., 2018). Furthermore, knowledge regarding habitat preferences and distribution pattern are needed for guiding conservation management for orchids (Djordjević et al., 2016; Margules and Pressey, 2000). In order to achieve this goal, we investigated the spatially suitable and unsuitable areas of four groups of orchids (lowland epiphyte, lowland terrestrial, upland epiphyte, upland terrestrial) under climate change and land cover change scenarios.

2. Methods

Orchids with a distribution range in mainland New Guinea were grouped into four classes based on elevation and life forms. These classes were epiphyte lowland, epiphyte upland, terrestrial lowland, and terrestrial upland (Table 1). The species was classified into four groups (lowland epiphyte, upland epiphyte, lowland terrestrial, upland terrestrial) because: 1). Some species of endemic orchids only have few known occurrence records, it is not possible to model each species due to small sample sizes, 2). Using the occurrence records of all species in the same group allows building and validating general model predictions, 3). The species grouping based on elevation (lowland and upland) reflects the distinct temperature and precipitation (climate factors) patterns of these regions. Although each species in the same group might have specific environmental requirements, regional variation of climate variables is likely to be consistently important.

The occurrence records of orchids were identified from direct field surveys, the Global Biodiversity Information Facility (GBIF) (GBIF,

Table 1
The endemic orchids of New Guinea.

Lowland epiphyte	Sample size	Upland epiphyte	Sample size	Lowland terrestrial	Sample size	Upland terrestrial	Sample size
<i>Bulbophyllum globulosum</i> (Ridl.) Schuit. & de Vogel	1	<i>Bulbophyllum peltopus</i> Schltr.	1	<i>Crepidium fissum</i> (Schltr.) Szlach	1	<i>Calanthe poiformis</i> P.J. Cribb & Ormerod	1
<i>Bulbophyllum latipes</i> J.J.Sm.	2	<i>Bulbophyllum leptoleucum</i> Schltr.	4	<i>Paphiopedilum glanduliferum</i> (Blume) Stein	1	<i>Dendrobium sleumeri</i> Ormerod	1
<i>Bulbophyllum mesodon</i> J.J.Verm.	2	<i>Bulbophyllum phormion</i> J.J. Verm.	9	<i>Calanthe pullei</i> J.J.Sm.	2	<i>Calanthe brassii</i> Ormerod	1
<i>Dendrobium poneroideis</i> Schltr.	9	<i>Bulbophyllum brachypetalum</i> Schltr.	4	<i>Spathoglottis bulbosa</i> Schltr.	1	<i>Collabium carinatum</i> de Vogel	2
<i>Dendrobium lasianthera</i> J.J.Sm.	8	<i>Mediocalcar bulbophylloides</i> J.J.Sm.	1	<i>Spathoglottis kenejiae</i> Schltr.	2	<i>Corybas naviculisepalus</i> P. Royen	1
<i>Dendrobium moiorum</i> Saputra, Schuit., Wanma & Naïve	5	<i>Dendrobium habbemense</i> P.Royen.	1	<i>Spathoglottis portus-finschii</i> Kraenzl.	4	<i>Thelymitra papuana</i> J.J. Sm.	9
<i>Dendrobium pseudocalceolum</i> J.J. Sm.	5	<i>Bulbophyllum cateorum</i> J.J.Verm.	1	<i>Corybas cyclopsensis</i> P.Royen	1	<i>Calanthe micrantha</i> Schltr.	5
<i>Dendrobium atroviolaceum</i> Rolfe	1	<i>Mediocalcar pygmaeum</i> Schltr.	1	<i>Corybas porphyryrus</i> P.Royen	1	<i>Crepidium distans</i> (Schltr.) Szlach.	2
<i>Bulbophyllum lagaroglossum</i> J.J. Verm.	1	<i>Dendrobium curvimentum</i> J.J.Sm.	1	<i>Corybas erythrocarpus</i> J.J.Sm.	1	<i>Corybas cymatilis</i> P.Royen	2
<i>Bulbophyllum digitatum</i> J.J.Sm.	1	<i>Bulbophyllum reevei</i> J.J. Verm.	1	<i>Crepidium lamii</i> (J.J.Sm.) M.A. Clem. & D.L.Jones	1	<i>Calanthe geelvinkensis</i> J.J. Sm	1
<i>Dendrobium aries</i> J.J.Sm.	1	<i>Bulbophyllum imitator</i> J. J.Verm.	1	<i>Crepidium raciborskii</i> (Szlach. & Marg.) Schuit. & de Vogel	1	<i>Cryptostylis apiculata</i> J.J. Sm.	1
<i>Dendrobium subquadratum</i> J.J. Sm.	1	<i>Bulbophyllum scopa</i> J.J. Verm.	3	<i>Crepidium rhabdophyllum</i> (Ridl.) Szlach.	1	<i>Cryptostylis arfakensis</i> J.J. Sm.	1
<i>Dryadorchis singularis</i> (J.J.Sm.) Christenson & Schuit.	1	<i>Bulbophyllum antennatum</i> Schltr.	5	<i>Crepidium graminifolium</i> (Schltr.) Szlach.	1	<i>Cryptostylis ligulata</i> J.J. Sm.	1
<i>Dendrobium violaceoflavens</i> J.J. Sm.	1	<i>Bulbophyllum brassii</i> J. J. Verm.	3	<i>Dendrobium lineale</i> Rolfe	11	<i>Spathoglottis parviflora</i> Kraenzl.	3
<i>Appendicula fasciculata</i> J.J. Sm	1	<i>Bulbophyllum simile</i> Schltr.	4	<i>Spathoglottis papuana</i> F.M.Bailey	11	<i>Calanthe fissa</i> L.O. Williams	9
	40		40		40		40

2022), the International Union for Conservation of Nature (IUCN) (IUCN, 2022), and scientific journals (Saputra, 2021). Each orchids' data, including the accepted name, occurrence, and distribution range were checked using online sources (De Vogel et al., 2022; Pfahl et al., 2022; POWO, 2022) and an orchid manual book (Ormerod, 2017). There are 160 occurrence records of orchids for all classes. Each class consisted of 15 species of orchids (Table 1).

A modelling approach was used to select the variables that best characterize the orchid habitats. Two categories of environmental variables (static and dynamic) were used to build the model. The static variables were topography and soil variables, while dynamic variables were climate and land cover variables. Elevation was extracted from Shuttle Radar Topography Mission (SRTM) Digital Elevation Models t available at 30 m spatial resolution (U.S. Geological Survey, 2022). Soil variables at 250 m spatial resolution from Global Digital Soil Mapping (SoilGrids) included soil organic carbon in dg/kg, nitrogen content in cg/kg, and soil pH (Hengl et al., 2017). Soil variables in the depth range of 5–15 cm were selected for terrestrial orchids, while soil variables in the depth range of 60–100 cm were selected for epiphyte orchids. Terrestrial orchids have small root system, typically <12 cm in length (Bingham, 2002), such as *Cymbidium* have a root depth about 2.5–7.5 cm (Wu et al., 2013). The soil variables in depth 60–100 cm were chosen based on the root depth of the epiphytic orchids' host trees.

The host trees of Genus *Bulbophyllum* include *Engelhardia roxburghiana* Wall. (Juglandaceae), *Meliosma squamulata* Hance (Sabiaceae), and *Machilus zuihoensis* Hayata (Lauraceae) (Martin et al., 2007). *Schima wallichii* is one of the host trees of the *Dendrobium* genus (Fardhani et al., 2020). *Nothofagus* species have been reported as host trees of the *Mediocalcar* genus. Other hosts of *Mediocalcar* include *Araucaria*, *Artocarpus*, *Castanopsis*, *Ficus*, *Lithocarpus*, and *Syzygium* (Schuiteman, 1997). Rooting depths of host trees are potentially important for predicting orchid habitat characteristics. Rooting depths have been identified for some host tree taxa: Fagaceae was about 94 cm (Hogan et al., 2020), Lauraceae was at 95 cm (Hogan et al., 2020), the genus *Artocarpus* was at 60–90 cm (Jamaludheen et al., 1997) and a 100 cm rooting depth was identified for the genus *Nothofagus* (Tate et al., 1993).

Climatic variables included annual mean temperature (°C), annual precipitation (mm), precipitation of wettest month (mm), and precipitation of driest Month (mm) available at 30 arc-second resolution (~1 km) which were derived from global climate data (Fick and Hijmans, 2017). The MRI-ESM2-0 Global Climate Model (GCM) (Yukimoto et al., 2019) with two scenarios for Shared Socioeconomic Pathways (SSPs) (SSP1–2.6 and SSP5–8.5) was used to model the projected suitable area changes for the 2080–2100 time period. SSP1–2.6 referred to a sustainable development scenario and SSP5–8.5 referred to a worst-case scenario with very high emissions. Land cover in 2020 represents our best estimate of the current land cover. These data were obtained from the Terra and Aqua combined Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type (MCD12Q1) Version 6 that was available at 500 m spatial resolution (Friedl and Sulla-Menashe, 2019). For future Land Cover predictions Land Cover in the year 2010 and in the year 2015 were used as a model calibration, while Land Cover in the year 2020 used as a model validation. The modelling process was run using "Molusce" tool in QGIS (Version 2.18.24) (Gismondini, 2013). The modelling process using different environmental layers as inputs of the model, but those variables are adjusted to represent a similar resolution and extent (Fig. 2). The final resolution of all environmental layers were adjusted at 30 arc-seconds (~ 1 km).

An ensemble model incorporating Random Forest (RF) (Breiman, 2001) and Support Vector Machine (SVM) (Noble and Street, 2006) components was used to predict current and future suitable areas of orchids under land cover and climate change. 80% of the data for each category (epiphyte lowland orchid, terrestrial lowland orchid, epiphyte upland orchid, and terrestrial upland orchid) were used to build the model. The R "dismo" and R "sdm" package were used to generate model predictions (Naimi and Araújo, 2016). The remaining 20% of the testing

data was used to validate model predictions. The Area Under Curve (AUC) evaluation metric and True Skill Statistics (TSS) were used to assess the performance of model predictions. The predictive map of current and future areas were classified into unsuitable (0–0.6) and suitable (0.6–1). The threshold value of 0.6 was derived from equal training sensitivity and specificity. The suitable areas from the current prediction was compared to future predictions to estimate change over time. The predictive maps of four groups of orchids (lowland epiphyte, lowland terrestrial, upland epiphyte, upland terrestrial) during three time periods (current, future (2100) using SSP 1–2.6, and future (2100) using SSP 5–8.5) were compared in order to identify the potential impact of climate change and land cover change on suitable areas for each group. Predicted suitable areas and elevation ranges were used as spatial change indicators.

3. Results

Historical occurrence records indicate that lowland orchids are mostly found in the northern part of the mountainous regions and the bird head of New Guinea, while upland orchids are mostly recorded in the central mountainous region extending from western to eastern of New Guinea (Fig. 1). Predictive current suitability maps for upland orchids cover a total area (235,752.19 km²) which is larger than that of the lowland orchids (180,174.81 km²). Lowland orchids were predicted to occupy an elevation range of about 0–1032 m, while upland orchid elevations ranged from 934 to 3995 m (Table 2).

This predicted elevation range of lowland and upland orchids were each aligned to the occurrence records with lowland orchids growing at <1000 m elevation and upland orchids growing at elevations >1000 m. The model generated current suitable maps showed that lowland epiphyte orchids are found mostly in southern and northern New Guinea and few areas in western New Guinea. Habitat characteristics of lowland terrestrial orchids are similar to those of the lowland epiphyte orchids that occupy mostly northern New Guinea and a few areas in southern and western New Guinea. Upland epiphyte orchids are found in mountainous regions of New Guinea from the west to the east. Upland terrestrial orchids are primarily found in the central mountainous region of eastern New Guinea (Fig. 3).

The predicted suitable areas for the lowland epiphyte group using SSP 1–2.6 expands by about 5.04% compared to the current predictive map. However, the suitable areas for other groups of orchids, including lowland terrestrial, upland epiphytic and upland terrestrial, are predicted to decline by 9.01%, 35.51%, and 19.59% respectively (Table 2). The lowest predicted elevation of the lowland orchids does not shift compared to the current suitable areas, but the upper elevation shifts upward by about 553 m. The lowest elevation of lowland terrestrial orchids shifts about 6 m lower, but the upper elevation range shifts upward by about 1091 m. For upland orchids, the lowest elevation of upland epiphytes shifts upward by about 158 m and the upper elevation range shifts slightly higher by about 20 m. In addition, the elevation range of upland terrestrial orchids shifts upward by about 171 m for the lowest elevation and 261 m for the highest elevation (Table 2). Lowland epiphyte orchids that are currently found mostly in southern and northern regions of New Guinea, tend to shift suitable areas to western New Guinea. Lowland terrestrial that are currently found in northern regions of New Guinea areas are predicted to shift from the northern to the eastern regions. Upland epiphyte orchids that are currently found in the central mountainous regions, are predicted to lose suitable habitats in the western regions. Upland terrestrial orchids are predicted to maintain suitable areas in the central mountainous region (Fig. 4).

Suitable areas of both lowland and upland terrestrial decrease in the future SSP 5–8.5 climate scenario. Lowland epiphyte orchids lose 16.66% of their suitable areas, 5.76% for lowland terrestrial, 11.63% for upland epiphyte and 79.23% for upland terrestrial (Table 2). The lower elevation boundary of lowland orchids does not shift compared to current suitable areas, but the upper elevation limit shifts higher by about

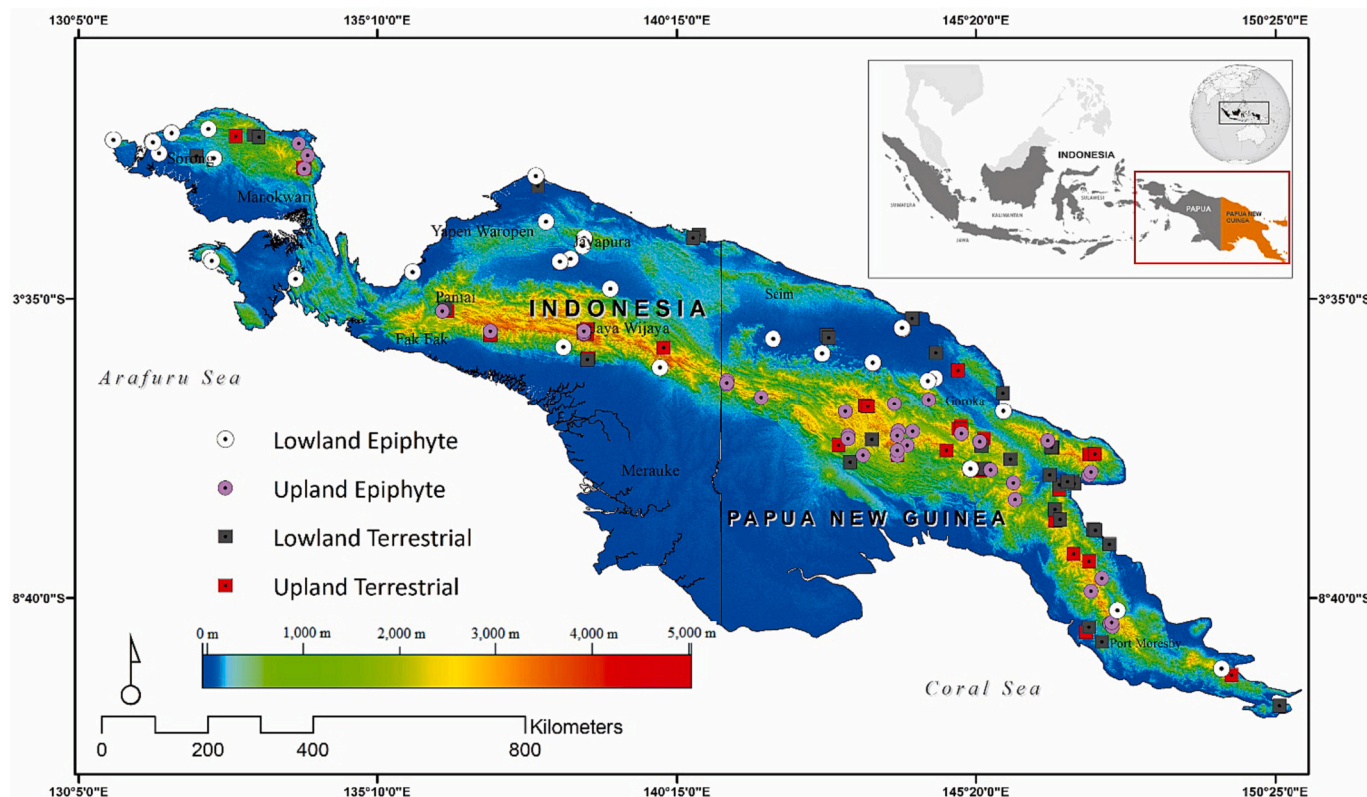


Fig. 1. Occurrence records of sampled lowland epiphyte, upland epiphyte, lowland terrestrial and upland terrestrial in New Guinea.

Table 2

Current and future suitable areas of four groups of orchids based on total areas and elevation range.

Groups of Orchid	current		ssp1-2.6_2100		ssp5-8.5_2100	
	areas (km ²)	elevation range (m)	areas (km ²)	elevation range (m)	Areas (km ²)	elevation range (m)
Lowland epiphyte	101,709.76	0–998	106,836.69	0–1501	84,766.67	0–1578
Lowland terrestrial	78,465.05	6–1032	71,392.27	0–2123	73,948.71	0–1891
Upland epiphyte	124,383.75	1046–3634	80,217.92	1204–3654	109,914.83	1105–3934
Upland terrestrial	111,368.44	934–3633	89,546.04	1105–3894	23,135.68	1260–3995

580 m. The lowest elevation range of lowland terrestrial orchids shifts lower by about 6 m, but the upper elevation increases by about 859 m. For upland orchids, the lower elevation limit of epiphytes increases by about 59 m and the upper elevation boundary shifts about 300 m higher. Additionally, the lower and upper predicted elevations limits of upland terrestrial orchids increase by about 326 m for the lower elevation limit and 362 m for the upper elevation boundary. Lowland epiphyte orchids are predicted to have suitable habitats in western, northern, eastern New Guinea and some areas in the southern region. Some currently suitable areas in southern New Guinea are predicted to disappear in the future SSP 5–8.5 scenario. For lowland terrestrial orchids, current suitable areas in western and northern New Guinea are predicted to disappear in the future SSP 5–8.5 scenario. The suitable areas for the upland epiphytic group does not change significantly in the central of mountainous region. Whereas, the suitable areas of upland terrestrial orchids in the western and eastern mountainous region are predicted to disappear (Fig. 5).

Variable importance analysis can be used to better understand the contributing factors that determine predicted suitable areas of each class of orchids in the future. In SSP 1–2.6 scenario, annual mean temperature and annual precipitation are two highest contributing factors affecting lowland epiphytes; annual mean temperature and precipitation of wettest month are the principal predictors for upland epiphytes; annual precipitation and elevation for lowland terrestrial; and annual mean

temperature and elevation for upland terrestrial orchids (Fig. 6). In the worst case SSP 5–8.5 climate change scenario precipitation of the wettest month and annual precipitation are identified as the two most important factors for lowland epiphytes; annual mean temperature and annual precipitation for upland epiphytes; precipitation of wettest month and elevation for lowland terrestrial; and annual mean temperature and precipitation of wettest month for upland terrestrial (Fig. 6).

4. Discussion

Ensemble models for all orchid groups have AUC values >0.90 and TSS > 0.80 for predicting current suitable areas. These models include almost 92% of the actual occurrence records for lowland epiphyte, 94% for lowland terrestrial, 96% for upland epiphyte, and 98% for upland terrestrial. Ensemble models also predict that the suitable areas for lowland epiphyte orchids cover 14.89% of the total New Guinea’s mainland area, 11.11% for lowland terrestrial, 18.83% for upland epiphyte, and 16.54% for upland terrestrial orchids. Lowland and upland orchids, either epiphytic or terrestrial, are predicted to respond to climate change and land cover change by shifting their suitable areas. The lowland epiphyte group is predicted to lose suitable areas in the worst case climate change scenario (SSP 5–8.5), but suitable areas for lowland orchids will expand in the most optimistic climate change scenario (SSP 1–2.6).

	Current prediction	Future prediction in 2100 (SSP 585)	Future prediction in 2100 (SSP 126)
Occurrence records			
Lowland terrestrial	<ul style="list-style-type: none"> Current climate <ul style="list-style-type: none"> Annual mean temperature Annual precipitation Precipitation of the wettest month Precipitation of the driest months Land cover in the year 2020 	<ul style="list-style-type: none"> Future climate <ul style="list-style-type: none"> Annual mean temperature Annual precipitation Precipitation of the wettest month Precipitation of the driest months Land cover in the year 2100 	<ul style="list-style-type: none"> Future climate <ul style="list-style-type: none"> Annual mean temperature Annual precipitation Precipitation of the wettest month Precipitation of the driest months Land cover in the year 2100
Upland terrestrial	<ul style="list-style-type: none"> Edephic in depth 5–15 cm <ul style="list-style-type: none"> Soil organic carbon Soil Nitrogen Soil pH Elevation 	<ul style="list-style-type: none"> Edephic in depth 5–15 cm <ul style="list-style-type: none"> Soil organic carbon Soil Nitrogen Soil pH Elevation 	<ul style="list-style-type: none"> Edephic in depth 5–15 cm <ul style="list-style-type: none"> Soil organic carbon Soil Nitrogen Soil pH Elevation
Lowland epiphyte	<ul style="list-style-type: none"> Current climate <ul style="list-style-type: none"> Annual mean temperature Annual precipitation Precipitation of the wettest month Precipitation of the driest months Land cover in the year 2020 	<ul style="list-style-type: none"> Future climate <ul style="list-style-type: none"> Annual mean temperature Annual precipitation Precipitation of the wettest month Precipitation of the driest months Land cover in the year 2100 	<ul style="list-style-type: none"> Future climate <ul style="list-style-type: none"> Annual mean temperature Annual precipitation Precipitation of the wettest month Precipitation of the driest months Land cover in the year 2100
Upland epiphyte	<ul style="list-style-type: none"> Edephic in depth 60–100 cm <ul style="list-style-type: none"> Soil organic carbon Soil Nitrogen Soil pH Elevation 	<ul style="list-style-type: none"> Edephic in depth 60–100 cm <ul style="list-style-type: none"> Soil organic carbon Soil Nitrogen Soil pH Elevation 	<ul style="list-style-type: none"> Edephic in depth 60–100 cm <ul style="list-style-type: none"> Soil organic carbon Soil Nitrogen Soil pH Elevation

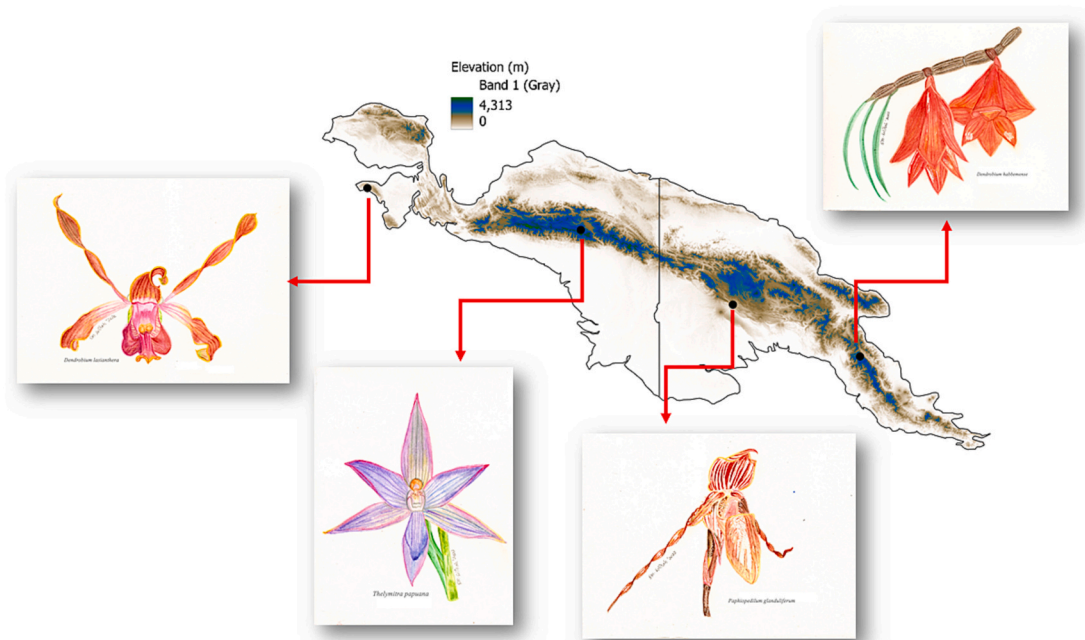


Fig. 2. Methodological visualization of the impact of future climate and land cover change to the vulnerability of orchids.

Suitable areas are predicted to expand to eastern New Guinea in the SSP 1–2.6 scenario with decreases of suitable areas mostly in northern New Guinea. The new suitable areas are primarily provide habitat for lowland orchids. The existence of suitable habitat does not ensure successful colonization from extant populations. Assisted migration might be an important conservation technique under these conditions. Lowland epiphytic orchids are predicted to shift to higher elevations in both in the SSP 1–2.6 and SSP 5–8.5 scenarios. As with the lowland terrestrial orchids, suitable areas for lowland epiphytic orchids are predicted to decrease and tend to shift to the higher elevations in the SSP 1–2.6 and SSP 5–8.5 climate scenarios. Lowland epiphyte orchids are very dependent on their host trees. The ecological requirements of host tree

species including soils, precipitation, and temperature, greatly influence the ecology of epiphyte orchids. The species composition and population structures of host tree species could limit the abundance of epiphyte orchids in the tropical dry forest (Vergara-torres et al., 2010). Lowland terrestrial orchids are limited by the canopy cover and some species of lowland terrestrial require a particular substrate to grow and survive. Lowland orchids (epiphyte and terrestrial) are vulnerable to anthropogenic disturbances. Human activities such as logging and land conversion have significant consequences for forest structure, composition, ecosystem functioning and biodiversity. The understory orchid *Wulfschlaegelia calcarata* was not found in areas with <20% canopy cover (Bergman et al., 2006). Some genera of orchids including *Acriopsis*,

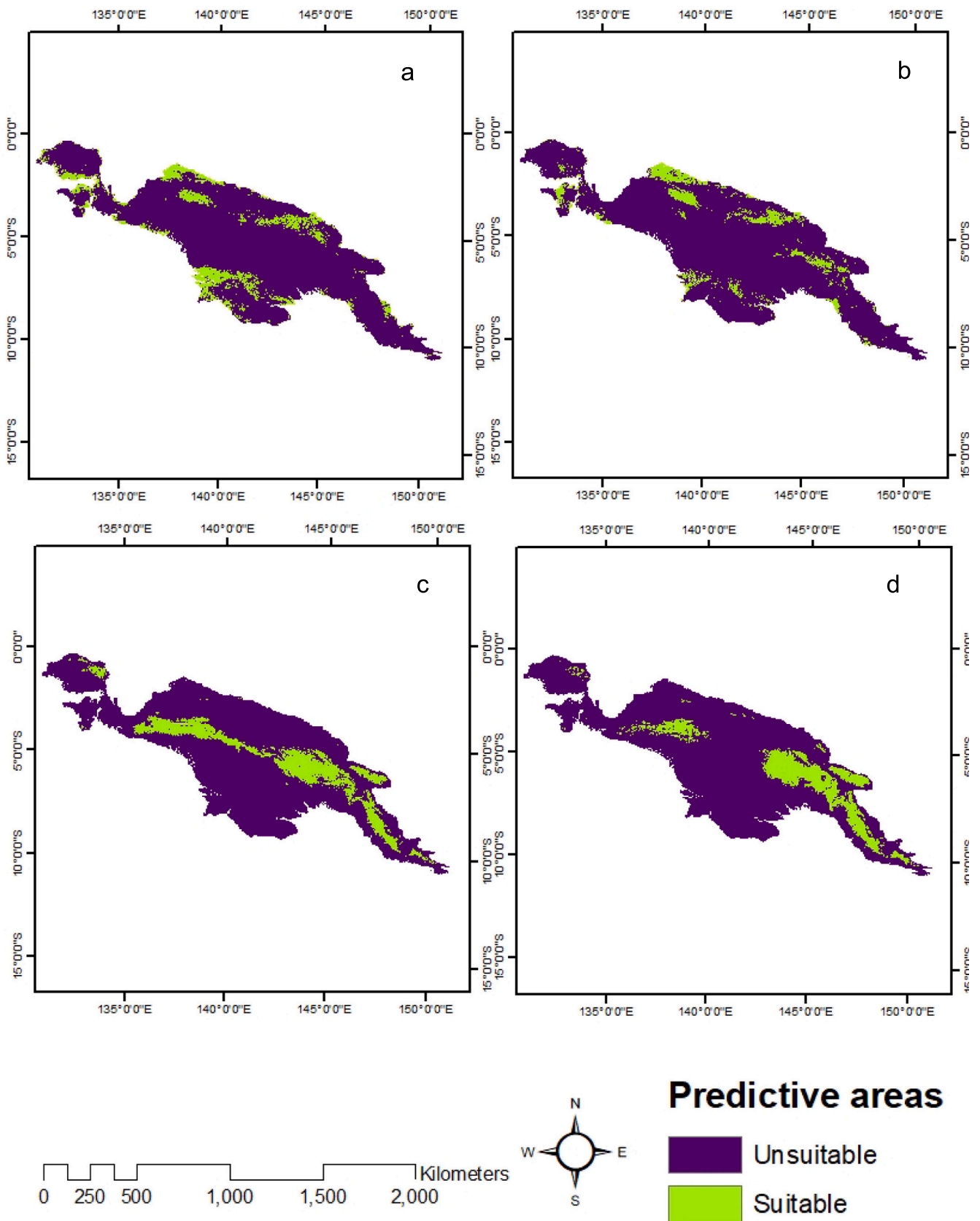


Fig. 3. Current potential suitable areas of New Guinea's Orchids: a). Lowland epiphyte, b). Lowland terrestrial, c). Upland epiphyte , d). Upland terrestrial.

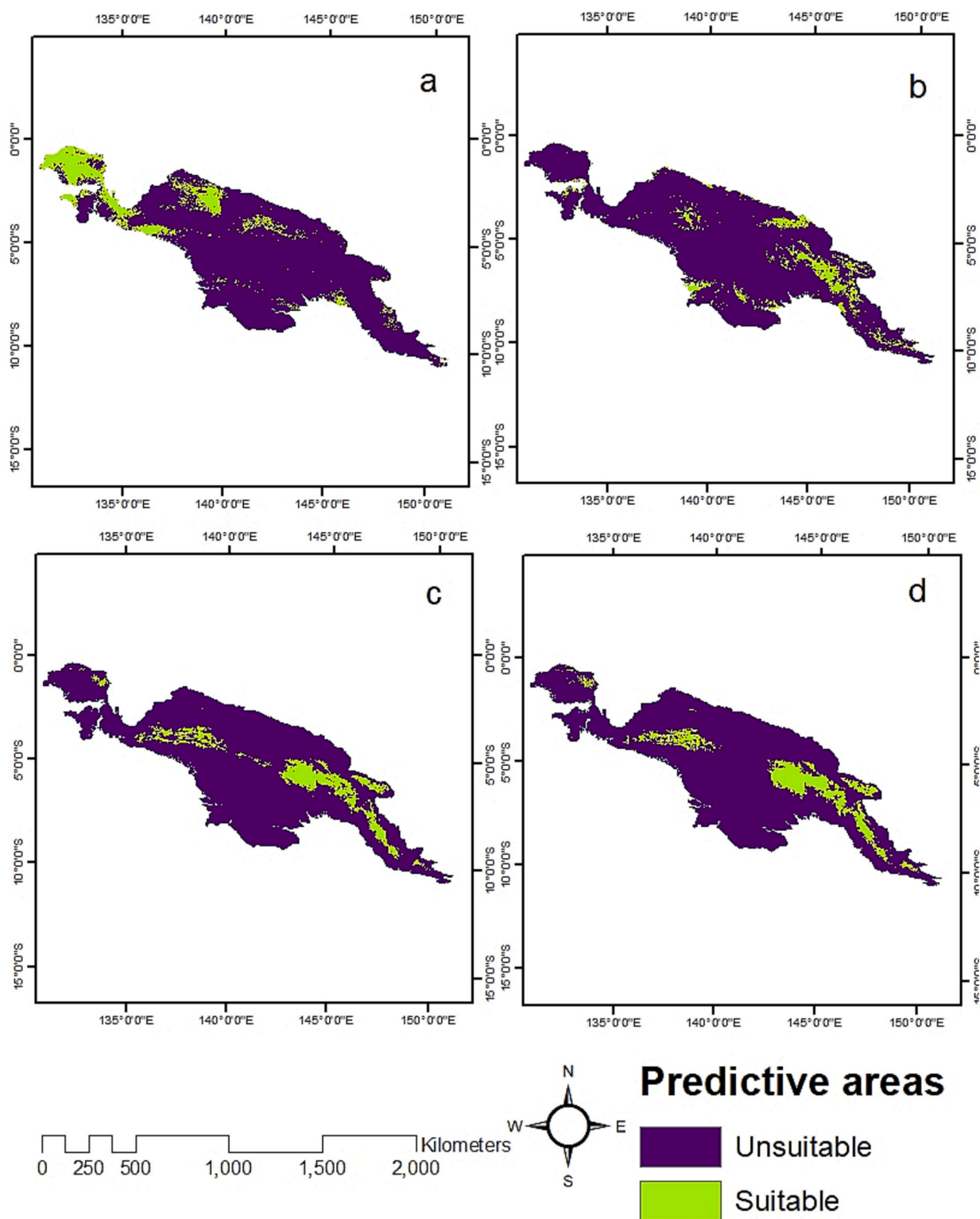


Fig. 4. Future potential suitable areas of New Guinea’s Orchids with SSP 1–2.6 climate scenario: a). Lowland epiphyte, b). Lowland terrestrial, c). Upland epiphyte, d). Upland terrestrial.

Cleisostoma, *Dendrobium*, *Bulbophyllum*, *Grammatophyllum*, *Phalaenopsis*, and *Pomatocalpa* are vulnerable to land use change (Böhnert et al., 2016).

The suitable areas of upland epiphyte and terrestrial orchids is predicted to decrease from current estimates in the SSP 1–2.6 and SSP 5–8.5 scenarios. The predicted elevation range of upland epiphyte orchids tends to shift higher in the SSP 5–8.5 scenario, but only slightly higher in

the 1–2.6 scenario. Upland terrestrial orchids are predicted to shift to higher elevations in the SSP 1–2.6 and SSP 5–8.5 climate scenarios. Upland terrestrial orchid species may grow in montane forests with high precipitation rate, high humidity and a dense canopy. The upland epiphyte depends on the availability of suitable tree hosts as well. When the tree host disappears due to climate and land cover change, the orchids will also disappear. A previous study of a montane orchid

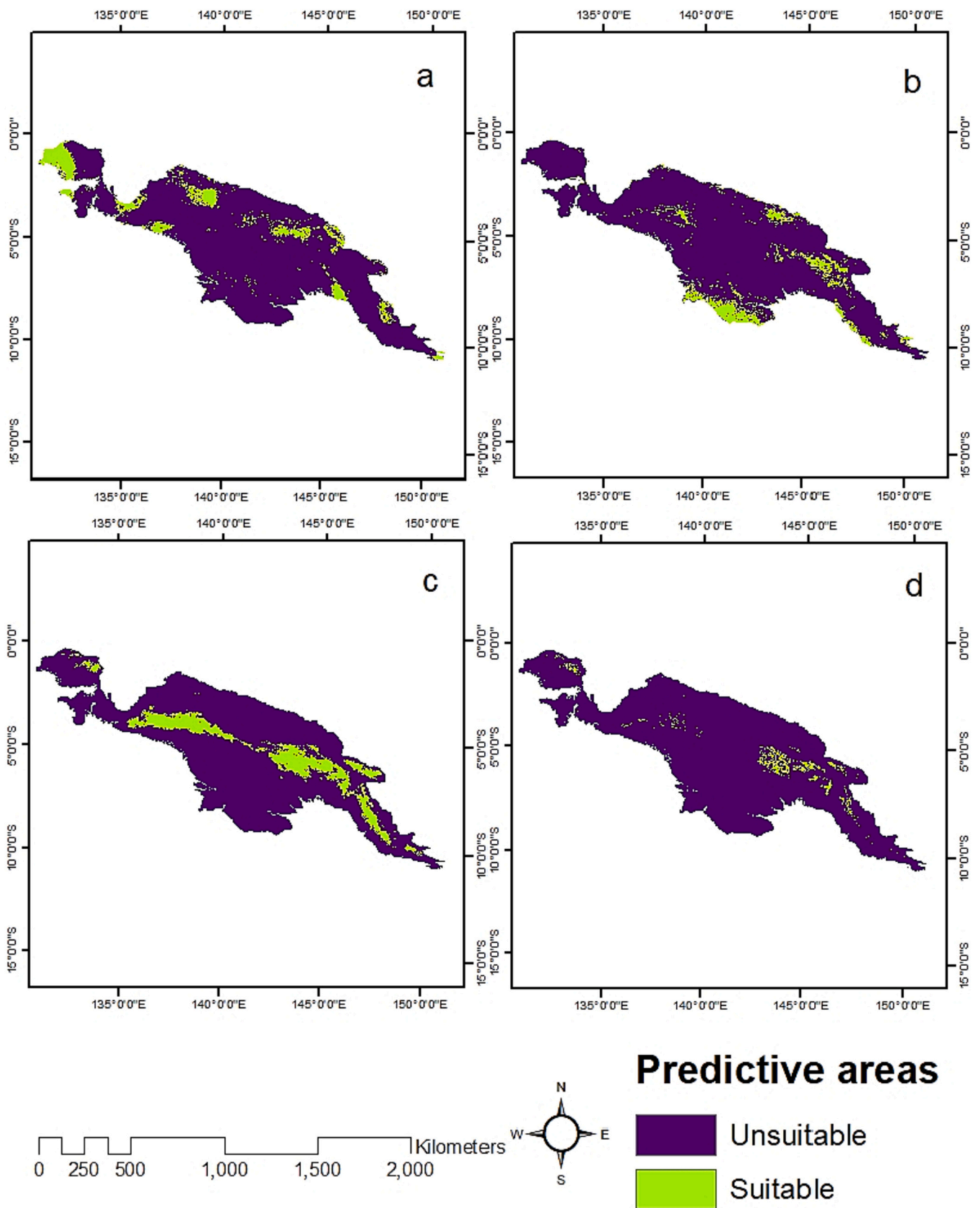


Fig. 5. Future potential suitable areas of New Guinea’s Orchids with SSP 585 climate scenario: a). Lowland epiphyte, b). Lowland terrestrial, c). Upland epiphyte, d). Upland terrestrial.

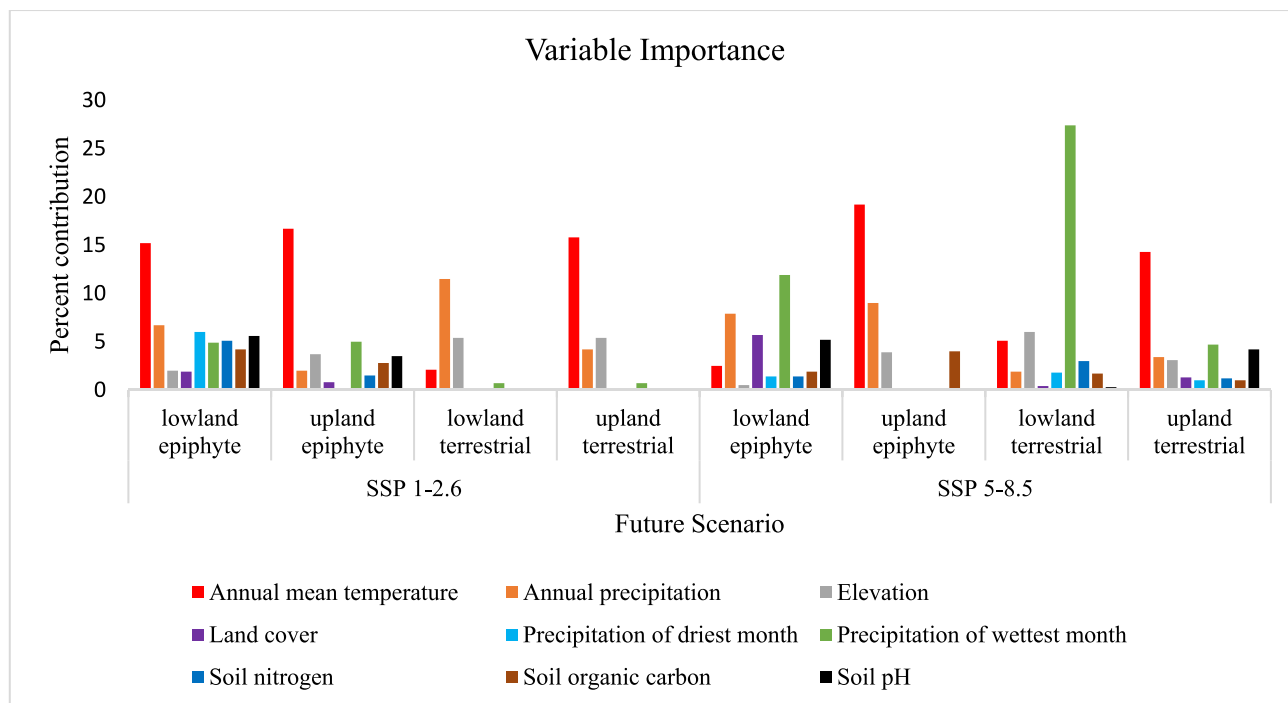


Fig. 6. Variable importance affecting the future suitability habitat of endemic orchids of New Guinea in their response to climate change and land cover change.

Traunsteinera globosa predicted a decrease of suitable habitats under a future climate scenario (Kolanowska, 2021). This pattern of decline has also been identified in a terrestrial orchid *Orchis militaris* that loses suitable habitat under climate change scenarios (Evans et al., 2020). In contrast, *O. anthropophora*, *O. purpurea* and *O. simia* were predicted to expand their suitable areas in the future (Evans et al., 2020). The vulnerability of species in biodiversity hotspots is a matter of concern. The central mountain region of eastern New Guinea is such a region with very high orchid species richness (Vollering and Raes, 2016).

Orchids, especially epiphytes, are extremely sensitive to climatic factors. Precipitation and vegetation cover were the best predictors of orchid hotspots which mainly occurs in mountainous regions and occasionally at lower elevations (Crain et al., 2020). A modelling study using 12 species in tropical dry forests in Colombia showed an altitudinal shifting compared from the present distribution, influenced by variables such as temperature, accessibility and precipitation, which suggested a vulnerability based on the connectivity between lowland and mid mountainous regions (Reina-Rodriguez et al., 2020). Evans et al. (2020) studied the impact of climate change on the distribution of four orchids. This study showed orchid species expand their distribution under mild climate change, however a temperature increase higher than 4 °C may lead to declines at lower latitudes. Vegetation cover was an important factor in addition to precipitation that determined orchid diversity hotspots in Costa Rica (Crain et al., 2020). Loss of vegetation cover significantly influences orchid diversity beneath the canopies because vegetation cover creates suitable habitats for both lowland and upland terrestrial orchids through protecting the soil surface, increasing soil organic matter, and reducing surface water runoff (Kosmas et al., 1999).

Land cover and land use changes from land clearing for agricultural development and selective logging of valuable timber species in West Africa, modifies the local habitats of epiphytes, affecting growth and survival, and increases population vulnerability (Pant, 2013; Pillon et al., 2007). Epiphytic orchids are very sensitive to environmental changes, species diversity tends to decrease along gradients from favorable moisture to the driest areas (Sanford, 1968). An epiphyte orchid, *Cymbidium tracyanum* that lives in tree canopies is more tolerant

to intense light exposure than *Cymbidium sinense* that is found on shady forest floors (Kuang and Zhang, 2015). The germination of many terrestrial orchids and some epiphyte orchids is restricted by the light environment (Rasmussen et al., 2015). The host trees traits such as the presence of allelopathic compounds, the life span of branches and diameter of trunk can limit the epiphyte establishment (Cortes-Anzúres et al., 2020; Zimmerman and Olmsted, 1992). Furthermore, the composition of forest host trees influences the abundance of epiphytes plants (Vergara-torres et al., 2010).

Two climatic factors (annual mean temperature and annual precipitation) are predicted to be the two most important factors for all orchid groups (epiphytic and terrestrial) in the SSP 1–2.6 climate scenario. Annual mean temperature and precipitation of the wettest month are the two most important predictors for all orchid groups in the SSP 5–8.5 climate scenario. As temperature increases, precipitation changes and land cover changes in the future, the suitable areas of lowland and upland orchids decreases and moves upward in elevation. Some species may adapt and tolerate the environmental change by moving to preferable habitats through dispersal mechanisms, but some are likely to disappear. Medicinal plant species are predicted to move upward in their distribution due to climate change (Manish, 2022). Furthermore, lowland orchids tend to be vulnerable to habitat destruction and over-exploitation of orchids. A previous study stated that some species of epiphyte orchids are harvested from lower montane cloud forest and illegally traded (Flores-palacios and Valencia-Diaz, 2007). Higher extraction rates of the orchid species *Laelia autumnalis* affects its population structure due to lower biomass accumulation and inflorescence development (Emeterio-lara et al., 2021). Incorporating physiological aspects, reproductive ability, and dispersal mechanisms with models of predicted suitable areas could be a useful approach to better understand and implement comprehensive assessments of the impact of climate change and land cover change to orchids. Assessing vulnerabilities of lowland and upland orchids is a critical step in the strategic conservation planning process that helps forest authority and conservationists identify key threats to resources.

5. Conclusion

Lowland epiphyte and terrestrial orchids are predicted to lose suitable habitat areas and shift to higher elevations in the year 2100 both in the SSP 1–2.6 and 5–8.5 climate scenarios. Suitable areas for upland epiphyte and upland terrestrial orchids are also predicted to decrease. Upland terrestrial orchids are predicted to have the largest loss of suitable habitat in the SSP 5–8.5 scenario from current know ranges. The suitable areas of upland epiphyte and terrestrial orchids are also predicted to shift to higher elevations.

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Declaration of competing interest

The authors declare no conflicts of interest.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

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