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A REGIONAL IUCN-BASED ASSESSMENT OF ORCHID SPECIES IN THE TROPICAL DRY FOREST OF VALLE DEL CAUCA, COLOMBIA

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Abstract. This study presents a regional conservation assessment of orchid species in the Tropical Dry Forest (TDF) of Valle del Cauca, Colombia. We compiled a curated dataset of 391 georeferenced occurrence records representing 50 species across 34 genera, integrating vouchered herbarium specimens, published literature, and observational records from biodiversity databases, subjected to record-by-record quality control. Extent of Occurrence (EOO) and Area of Occupancy (AOO) were estimated following IUCN Red List Criterion B. To evaluate subcriteria B(a) (severe fragmentation) and B(b)(iii) (continuing decline in habitat area and quality), we applied an improved version of the EECORisk pipeline. This pipeline integrates Hansen Global Forest Change (GFC) data to assess habitat patch configuration and detect ongoing forest loss (2001–2023) around species occurrences. Of the 50 assessed species, seven were categorized as Critically Endangered (CR), 23 as Endangered (EN), 14 as Vulnerable (VU), and six as Least Concern/Near Threatened (LC/NT) at the departmental scale, underscoring the severity of habitat loss and fragmentation in TDF remnants. Orchid richness peaked between 900 and 1300 m a.s.l., and localities such as Hacienda El Medio (Zarzal) emerged as key areas concentrating records and richness. Overall, these results demonstrate the utility of the EECORisk pipeline for transparent, reproducible regional conservation assessments and underscore the need to prioritize habitat protection, connectivity restoration, and targeted monitoring in fragmented TDF ecosystems.

Resumen. Este estudio presenta una evaluación regional del riesgo de extinción de las orquídeas en los remanentes del Bosque Seco Tropical (Bs-T) del Valle del Cauca, Colombia. Compilamos un conjunto de datos curado de 391 registros georreferenciados de ocurrencia que representan 50 especies en 34 géneros, integrando especímenes de herbario, literatura publicada y registros observacionales de bases de datos de biodiversidad, sometidos a control de calidad registro por registro. La Extensión de Ocurrencia (EOO) y el Área de Ocupación (AOO) se estimaron según el Criterio B de la Lista Roja de la UICN. Para evaluar los subcriterios B(a) (fragmentación severa) y B(b)(iii) (disminución continua del área y calidad del hábitat), aplicamos una versión mejorada del pipeline EECORisk. Este pipeline integra datos de Hansen Global Forest Change (GFC) para evaluar la configuración de parches de hábitat y detectar la pérdida continua de bosque (2001–2023) alrededor de las ocurrencias de las especies. De las 50 especies evaluadas, siete fueron categorizadas como En Peligro Crítico (CR), 23 como En Peligro (EN), 14 como Vulnerable (VU) y seis como Preocupación Menor/Casi Amenazado (LC/NT) a escala departamental. La riqueza de orquídeas alcanzó su máximo entre 900 y 1300 m s.n.m. y localidades como Hacienda El Medio (Zarzal) emergieron como áreas clave que concentran registros y riqueza. Estos resultados demuestran la utilidad del pipeline EECORisk para evaluaciones regionales transparentes y reproducibles del riesgo de extinción de orquídeas y resaltan la necesidad de priorizar la protección de hábitats, la restauración de la conectividad y los monitoreos localizados en ecosistemas fragmentados del Bs-T.

Keywords / Palabras clave: análisis espacial, conservación de orquídeas, Criterio B UICN, disminución de hábitat, EECORisk, extinction risk, habitat decline, Hansen Global Forest Change, IUCN Criterion B, orchid conservation, riesgo de extinción, spatial analysis

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Introduction. Tropical Dry Forests (TDFs) are among the most critically endangered ecosystems both in Colombia and globally. They are characterized by annual precipitation ranging from 250 to 2000 mm, with pronounced seasonality leading to extended dry periods (Espinal & Montenegro, 1963; Linares & Fandiño, 2009), and by one or two dry seasons where potential evapotranspiration exceeds precipitation (DryFlor, 2016). TDFs hold significant ecological value due to their high levels of biodiversity and the essential ecosystem services they provide, such as carbon sequestration, soil stabilization, and habitat for unique flora and fauna; recent evidence has also shown that these forests support socio-ecological resilience by underpinning rural livelihoods and regulating watershed dynamics in regions facing increasing aridity (Norden *et al*., 2021). Historically, TDFs in Colombia covered approximately 9 million hectares; however, less than 8% of their original extent remains today, representing about 720,000 hectares (Etter *et al*., 2008; Pizano & García, 2014). Current assessments indicate that only 5% of the remaining TDF fragments are under any legal protection, and mature forest is nearly absent, with most fragments being in early or intermediate successional stages (González-M. *et al*., 2018).

The Valle del Cauca, a department notably rich in biodiversity, has undergone particularly intense transformation of its dry forests, primarily driven by the expansion of industrial crops, such as sugarcane, extensive cattle ranching, and urbanization (Montano Fuentes *et al*., 2022; Uribe-Castro, 2015). These transformations have led to significant habitat loss and degradation, resulting in reduced biodiversity and fragmented ecosystems (Fig. 1). By 1957, dry forests covered approximately 6% of their original extent in the Geographical Valley of the Cauca River; however, by 1986, this coverage had declined to just 2% (CVC, 2000). Currently, less than 1% of these forests remain in scattered fragments, underscoring the urgent need for conservation measures (Vargas, 2012). Despite the fertility of its alluvial soils, which has driven intensive agriculture, small fragments of native vegetation persist, covering less than 500 hectares and scattered across an agriculturally dominated landscape. These remnant patches are often isolated and irregularly shaped, further limiting their ecological functionality (González-M. *et al*., 2018). Such fragmentation in the TDF creates "islands" of habitat surrounded by anthropogenic matrices, a scenario that calls for spatial analyses to identify priority conservation areas (Galindo *et al*., 2005) and aligns with the island biogeography framework for understanding species richness in these forests relicts (Soto-Medina *et al*., 2023). In 2018, Ramos and Silverstone conducted a comprehensive study in the Geographical Valley of the Cauca River, documenting plant collections from these fragments between 1986 and 2009. The study recorded 950 vascular plant species across 38 sites, of which 60.8% were identified as forest species, thereby highlighting the significant biodiversity still present in these remnants. These findings suggest that the total flora of the geographical valley may include approximately 2000 species (Ramos & Silverstone, 2018; Vargas, 2012).

Within this context, the Orchidaceae family, one of the most emblematic and diverse plant families in the TDF, faces severe threats. Colombia and Ecuador are the countries with the highest diversity of orchid species, with over 4000 registered species (Pérez-Escobar *et al*., 2024). In the Valle del Cauca, around 71 orchid species have been documented within TDF fragments, of which 10 are endemic, underscoring the critical role of this region in biodiversity conservation (Ramos & Silverstone, 2018; Reina-Rodríguez *et al*., 2016). However, the uniqueness of orchid diversity in each region is further accentuated by the high beta diversity and floristic turnover reported for the TDF across Colombia, where species assemblages differ markedly between regions, reinforcing the need for region-specific conservation actions (DryFlor, 2016; Kattan *et al*., 2019). At the national scale, orchids comprise a significant portion of the Red List assessments, with approximately 52% of evaluated species identified as threatened (López-Gallego *et al*., 2024).

Climate change represents an emerging threat that may further exacerbate the already precarious status of TDF orchids through warming, shifts in rainfall regimes, and an increasing frequency of extreme weather events. González-M. *et al*. (2021) studied the effects of the ENSO (El Niño–Southern Oscillation) 2015 and showed that ecological functionality and biomass gain would be reduced if dry conditions increase. For orchids specifically, temperature increases can lead to heat stress, impairing growth and reducing flowering success (Benzing, 1998; Crain &

Figure 1. Typical landscape of the geographical Cauca River Valley in Valle del Cauca, Colombia, showing extensive agricultural transformation dominated by sugarcane cultivation. The image illustrates the characteristic matrix of anthropogenic land use in which Tropical Dry Forest remnants are embedded. Photograph by J.S. Moreno.

Tremblay, 2017; Zotz & Bader, 2009). Altered rainfall patterns can cause prolonged droughts, limiting water availability crucial for orchid survival (de la Rosa-Manzano *et al*., 2014). Recent models highlight that even small shifts in temperature and precipitation patterns can critically impact the persistence of TDF plant communities, particularly given their narrow ecological tolerances and limited dispersal capacity in highly fragmented landscapes (González-M. *et al*., 2018; Reina-Rodríguez *et al*., 2017). Elevation is also a key axis structuring orchid occurrence in seasonally dry landscapes because it integrates strong gradients in temperature, humidity, cloud/fog inputs, and canopy microclimate over relatively short geographic distances. For TDF orchids, shifts in these gradients can compress suitable microclimates, making mid-elevation sites critical both as current diversity hotspots and as potential refugia under climate change scenarios (Crain & Tremblay, 2017).

Despite the ecological importance of orchids in TDF remnants, none of these species has been regionally assessed for Valle del Cauca under the IUCN criteria. Regional assessments can provide more decision-relevant information than global categorizations because they explicitly capture localized pressures, habitat configuration, and jurisdiction-specific management constraints. Importantly, conservation priorities may be underestimated when taxa are relatively widespread elsewhere but locally rare within a given jurisdiction, especially because land-use decisions and conservation actions are frequently implemented at local and regional scales (Crain & White, 2011). In this context, incorporating the concept of local rarity helps to anticipate potential discrepancies between global status and local extinction risk, particularly for taxa confined to small, fragmented habitat patches (Crain & Tremblay, 2012). Currently, it is estimated that 40% of plant species are globally threatened with extinction (Nic Lughadha *et al*., 2020), yet less than 15% of global plant diversity has been evaluated for the Red List (IUCN, 2024). In Colombia, the first published effort to categorize orchid species using IUCN criteria was conducted by Calderón (1998), which included 128 species. In 2006, Calderón-Sáenz addressed these limitations in volume 6 of the Red Books of Plants of Colombia, evaluating 375 species and categorizing 207 of them as threatened to varying degrees (Ministerio de Ambiente y Desarrollo Sostenible & Universidad Nacional de Colombia, 2015).

Given the critical condition of the TDF in Valle del Cauca, this study aims to systematically categorize the orchid species present in these remnants based on IUCN Criterion B and by applying the EECORisk pipeline to evaluate geographic range metrics, severe fragmentation, and continuing habitat decline (Arango & López-Gallego, 2023). Beyond producing regional IUCN Criterion B assessments, we use the results to identify taxa that emerge as locally critical conservation priorities and to outline actionable management pathways. These pathways include *in situ* measures (e.g., habitat protection and connectivity) and complementary *ex situ* options (e.g., propagation and population reinforcement) where local extinction risk is elevated.

Materials and methods. *Biological data.—* This study compiled data on the occurrence of orchid species in the Tropical Dry Forest (TDF) of Valle del Cauca Department, Colombia. Data sources included vouchered specimens from national herbaria (CAUP, CUVC, FMB, HPUJ, HUA, JAUM, JBB, MO, SALLE, SEL, VALLE, and TOLI), which were selected due to their extensive collections of plant specimens from the region and their historical importance in documenting orchid diversity, especially in the tropical dry forests of Valle del Cauca Department. Scientific literature, notably studies by Ramos and Silverstone (2018); Reina-Rodríguez (2012, 2016): Reina-Rodríguez *et al.* (2016, 2017), and Vargas (2012). Digital platforms (GBIF, 2025; Tropicos, 2025), and the CEIBA/I2D resource of the Alexander von Humboldt Institute (Instituto Humboldt & Universidad del Valle, 2015), from which only the Orchidaceae subset attributable to Valle del Cauca was incorporated.

Given the high taxonomic complexity of Orchidaceae and the frequency of misidentifications in occurrence datasets, all records were curated individually prior to inclusion. We applied a tiered evidence framework in which records were retained based on the strength of supporting information rather than the presence of any single field. Herbarium records were prioritized because voucher specimens provide taxonomically verifiable evidence even when photographs are unavailable; nonetheless, locality precision and taxonomic reliability were evaluated in each case. For records without herbarium vouchers (i.e., occurrence data compiled from published literature and biodiversity databases), all entries were manually reviewed, including photographs (when available) and coordinates, and records were retained only when images or descriptions allowed diagnostic identification and when locality, habitat, and elevational context were ecologically plausible for TDF orchids. Spatial quality control was conducted in R using CoordinateCleaner (Zizka *et al*., 2019) to flag common geographic issues, followed by manual verification of flagged records. Records lacking coordinates were georeferenced following Escobar *et al*. (2015). This workflow ensured that the final dataset reflected only records that were taxonomically and spatially defensible for analyses of orchid diversity and conservation status. Generic circumscriptions within Maxillariinae follow the phylogenetic classification of Blanco *et al*. (2007), who segregate several genera from *Maxillaria s.l.*

Mapping and richness patterns.— All orchid distribution records were organized into a database to quantify species richness at the municipal level and to identify endemic species. Mapping was conducted in QGIS v3.28 (QGIS Development Team, 2023).

Elevational patterns of species richness.— To describe elevational patterns in orchid richness within TDF remnants, we analyzed georeferenced orchid records from the study area to assess the relationship between species richness and elevation. Elevation data were assigned from record metadata or extracted from digital elevation models. Data were grouped into 50-meter elevation intervals. Species richness was calculated as the number of unique species present within each elevation interval. We generated a smoothed curve using cubic spline interpolation to visualize trends in species diversity across elevation gradients. A histogram was constructed to depict the distribution of records across elevation intervals.

Categorization based on IUCN criteria.— We applied the IUCN Red List Categories and Criteria (IUCN, 2024) to assess extinction risk under Criterion B (Geographic Distribution). Criterion B evaluates two complementary range metrics: (1) Extent of Occurrence (EOO; B1), which is the area encompassed within the shortest imaginary boundaries containing all known sites of a species, calculated using a minimum convex polygon (IUCN, 2017); (2) Area of Occupancy (AOO; B2), defined as the area effectively occupied by a species within the EOO, estimated by counting occupied 2 × 2 km grid cells following IUCN standards.

To generate automated conservation assessments for these metrics, the R package ConR v1.2.2 was utilized (Dauby *et al*., 2017). ConR was chosen for its efficiency in calculating key conservation metrics such as EOO and AOO from georeferenced occurrence data. All range metrics are based on observed occurrences, with records lacking coordinates georeferenced from locality descriptions following Escobar *et al.* (2015). Species with fewer than three georeferenced records were included in assessments, as habitat decline metrics can be evaluated even for single-locality occurrences using the EECORisk pipeline detailed below.

Under Criterion B, a species qualifies for a threat category when its geographic range falls below established thresholds (B1: EOO < 100 km² for CR, < 5000 for EN, < 20,000 for VU; B2: AOO < 10 km² for CR, < 500 for EN, < 2000 for VU) and at least two of three additional subconditions are met: (a) severely fragmented or number of locations at or below the category threshold (CR ≤ 1, EN ≤ 5, VU ≤ 10); (b) continuing decline observed, estimated, inferred, or projected in any of: (i) EOO, (ii) AOO, (iii) area, extent, and/or quality of habitat, (iv) number of locations or subpopulations, (v) number of mature individuals; (c) extreme fluctuations.

EECORisk pipeline: implementation and improvements.— To evaluate subcriteria B(a) and B(b)(iii) in a transparent and reproducible manner, we built upon the EECORisk pipeline (Arango & López-Gallego, 2023), an R-based framework developed by the Colombian Plant Specialist Group (GEPC) of the IUCN for national Red List assessments of plants in Colombia. The original EECORisk calculates EOO, AOO, number of locations, and subpopulations, and evaluates severe fragmentation B(a) and continuing decline B(b)(iii) using national-scale maps of forest cover (IDEAM, 2016) and the human footprint index (Correa-Ayram *et al*., 2020), as applied to over 3000 species for the national Red List (López-Gallego & Morales-Morales, 2023; López-Gallego *et al*., 2024). In the original implementation, severe fragmentation is inferred from forest-patch sizes at occurrence localities, and continuing decline is determined primarily from changes in the human footprint index between two time periods. For the present study, we adapted the pipeline to the regional scale and increased the temporal resolution of the habitat decline assessment by implementing the improvements detailed in each module below. The pipeline operates in four sequential modules:

1. Geographic metrics (EOO, AOO, locations, subpopulations). EOO and AOO were calculated as described above using ConR. Locations are counted as the number of occupied cells in a threat grid reflecting the spatial scale at which a single threatening event can affect all individuals (default 10 × 10 km). For species whose distributions overlap with intensive agricultural areas (particularly industrial sugarcane monoculture), a 20 km grid cell size was used to reflect the landscape-scale operation of this threat. Subpopulations are identified as clusters of occurrences within a 10 km radius using graph-based connectivity analysis.

2. Severe fragmentation [B(a)]. Using Hansen Global Forest Change (GFC) treecover2000 data (Hansen *et al*., 2013)—which provides annual, pixel-level (30 m) information on baseline tree cover and year of forest loss (lossyear, 2001–2023)—the pipeline identifies habitat patches around species occurrences by classifying pixels with ≥30% tree cover as potential habitat. This replaces the national IDEAM forest-cover map used in the original pipeline, providing finer spatial resolution suitable for the small, highly fragmented TDF remnants of Valle del Cauca. Patches are delineated using connected-component analysis, and each patch is characterized by its area and distance to the nearest neighboring patch. A species is considered severely fragmented when >50% of its subpopulations occur in patches that are both small (<1 km²) and isolated (>10 km from the nearest patch), thresholds parameterized specifically for TDF orchids to reflect the characteristically small size of remnants in the region and the limited dispersal capacity of most epiphytic and terrestrial orchid species.

3. Continuing decline in habitat [B(b)(iii)]. Using Hansen GFC lossyear data, the pipeline quantifies forest loss within a 5 km buffer around all occurrences of each species over the period 2001–2023. Rather than the single metric used in the original pipeline (change in human footprint between two periods), we implemented three independent, complementary criteria applied to the annual loss time series: (C1) forest loss detected in ≥3 of the last 10 years (2014–2023), indicating sustained and ongoing loss; (C2) cumulative forest loss ≥2% AND loss detected in the last 5 years (2019–2023), capturing significant total loss with recent activity; (C3) loss rate in the recent period (2014–2023) exceeding the previous period (2001–2013),

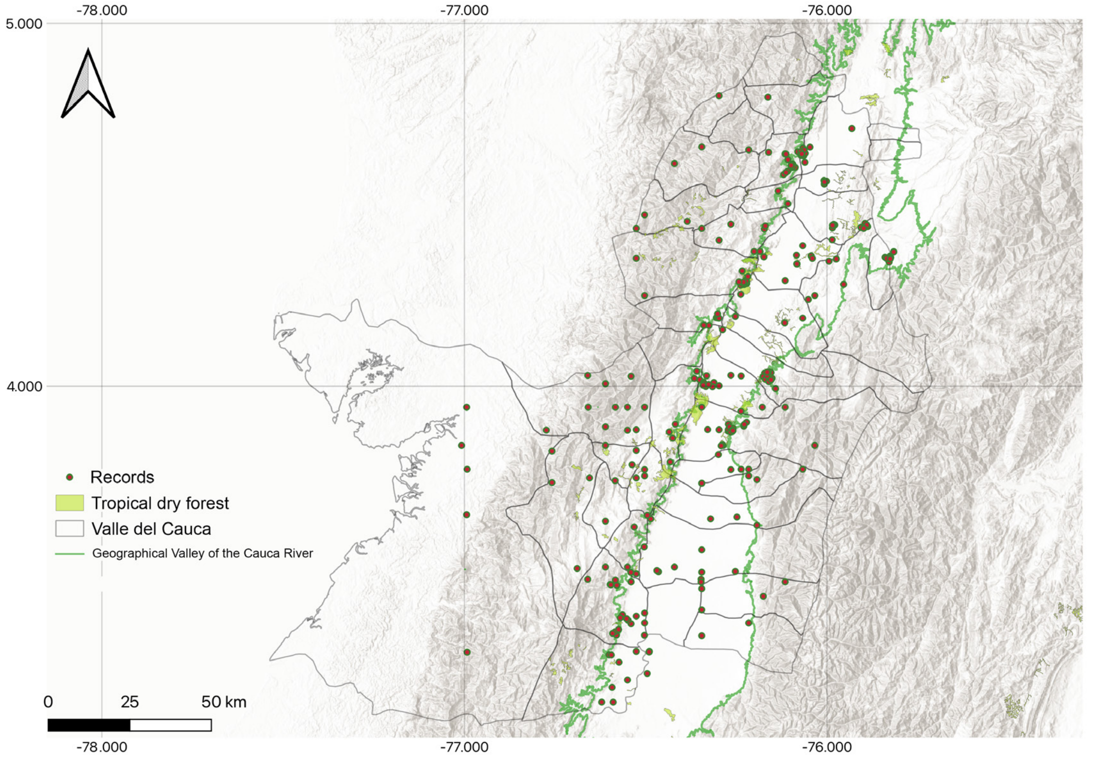

FIGURE 2. Distribution of orchid records within the Tropical Dry Forest remnants of Valle del Cauca, Colombia. The map shows the geographical Cauca River Valley, protected areas (in green), municipalities boundaries (black lines), and the location of 391 georeferenced orchid records (brown dots) used in this study.

detecting accelerating decline. A species is scored as exhibiting continuing decline if any criterion is met. This multi-criteria approach reduces the risk of both false positives (one-time events misclassified as continuing) and false negatives (slow but persistent loss going undetected).

4. Final categorization. Each species is assigned to the most severe IUCN category for which it meets the geographic-range prerequisite (B1 and/or B2) and at least two subconditions from: (a) severely fragmented or number of locations at or below the category threshold, or (b) continuing decline. The subcriteria contributing to the final category are reported explicitly (e.g., EN B1+B2ab(iii)). Per-species maps showing occurrence points, EOO polygons, AOO grids, and forest-loss footprints are generated for complete transparency.

Results. In this study, we compiled a total of 391 records corresponding to 50 species (including six endemic taxa) distributed across 34 genera in Valle del Cauca (Fig. 2; Supplementary Table S1). Of these, 25 genera were monospecific. *Epidendrum* L. was the most species-rich genus with eight species, followed by *Encyclia* Hook. with three species. Seven additional genera contained two species each: *Catasetum* Rich. ex Kunth, *Cyclopogon* C.Presl, *Eulophia* R.Br., *Heterotaxis* Lindl., *Rodriguezia* Ruiz & Pav., *Sobralia* Ruiz & Pav., and *Vanilla* Mill. Among the endemic taxa recorded, *Catasetum tabulare* Lindl. and *Epidendrum lambeauanum* De Wild. are included here as illustrative examples (Fig. 3–4). The herbarium collection CUVC held the largest share of voucher-based records (n = 170), followed by TULV (n = 9) and VALLE (n = 6), with additional vouchers contributed by SALLE (n = 3), CAUP (n = 1) and COL (n = 1); the remaining records (n = 201) correspond to occurrence data from published inventories and observational sources without herbarium vouchers (Fig. 5).

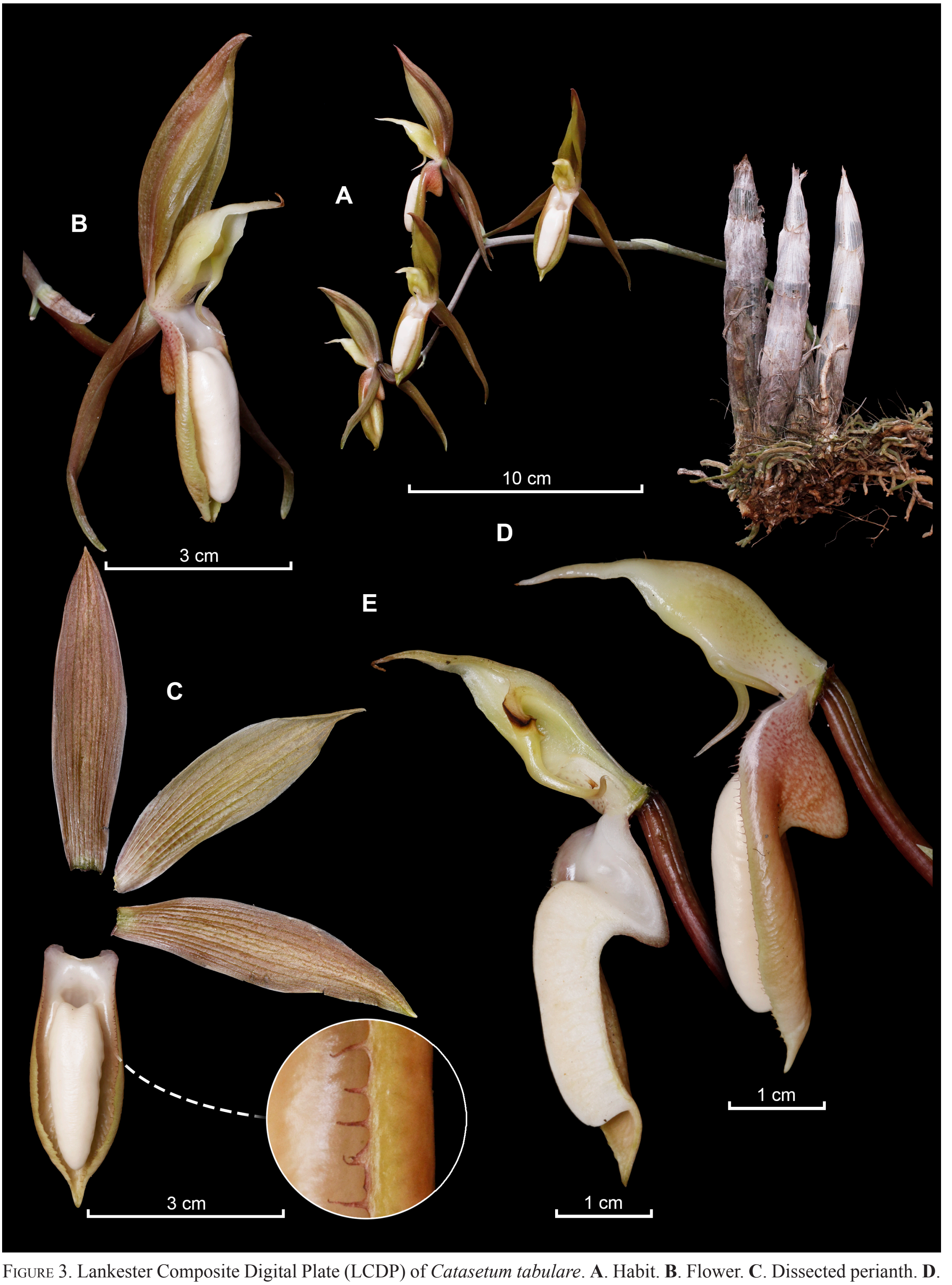

Figure 3. Lankester Composite Digital Plate (LCDP) of *Catasetum tabulare*. **A**. Habit. **B**. Flower. **C**. Dissected perianth. **D**. Column and lip, lateral view. **E**. Column and lip, longitudinal section. LCDP by E. Restrepo.

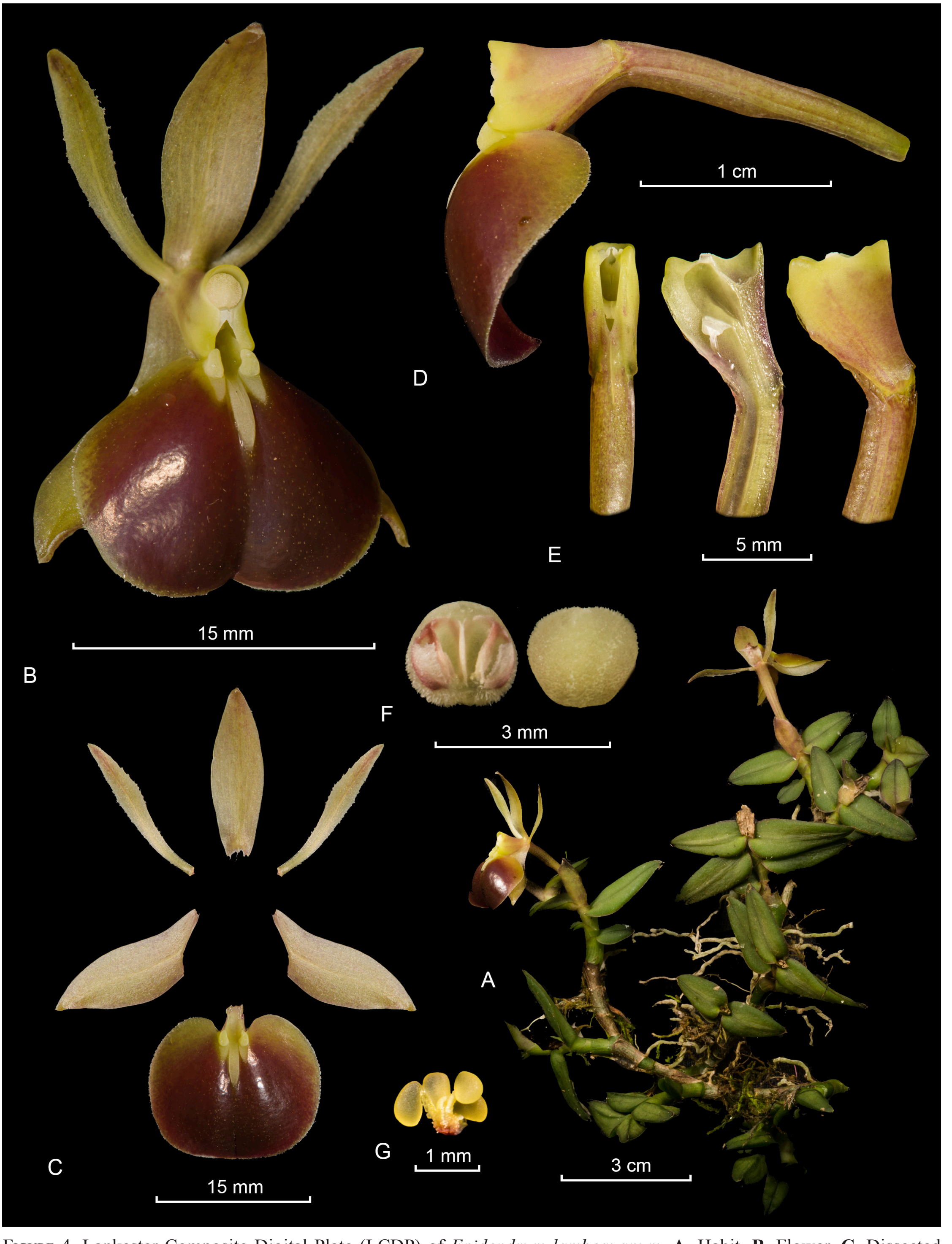

Figure 4. Lankester Composite Digital Plate (LCDP) of *Epidendrum lambeauanum*. **A**. Habit. **B**. Flower. **C**. Dissected perianth. **D**. Column and lip, lateral view. **E**. Column, ventral, longitudinal section, and lateral views. **F**. Anther cap. **G**. Pollinarium. LCDP by J.S. Moreno, from Hágsater (2018: Plate 1633).

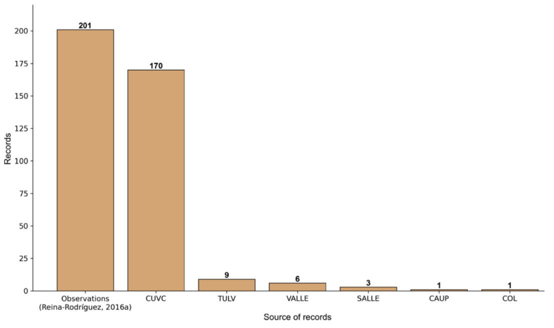

Figure 5. Distribution of the 391 orchid records compiled in this study according to source: herbarium vouchers (CUVC, TULV, VALLE, SALLE, CAUP, COL) and observational records from published inventories and biodiversity databases without herbarium vouchers.

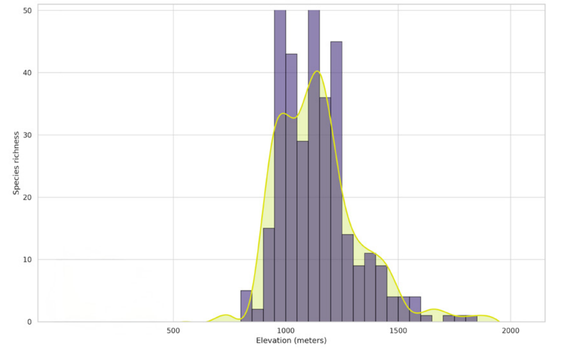

Figure 6. Altitudinal distribution of orchid species richness based on the 391 georeferenced records compiled in this study. Purple bars represent the number of records within each 50-meter elevation interval. The yellow smoothed curve was generated using cubic spline interpolation to visualize trends in species richness across elevation gradients, highlighting elevational ranges with highest diversity. The shaded yellow area under the curve represents the cumulative distribution of species richness, indicating the probability density of orchid species occurrence across the elevational gradient.

Across municipalities, records were most numerous in Zarzal (23 spp.; n = 59), followed by Buga (22 spp.; n = 37), Cali (14 spp.; n = 34), Toro (17 spp.; n = 34), and Yotoco (17 spp.; n = 31). Tuluá (21 spp.; n = 26), Caicedonia (14 spp.; n = 24), and La Victoria (16 spp.; n = 22) also showed significant representation. At the locality level, Hacienda El Medio (Zarzal; 944 m a.s.l.) concentrated the highest number of records across the study region, with 17 records representing 12 species, consistent with previous inventories (Reina-Rodríguez, 2016). These values should be interpreted considering the historically intensive sampling effort at this site (Ramos & Silverstone, 2018). Species richness peaked between 900 and 1300 m in elevation (Fig. 6).

Regional categorization according to IUCN criterion B.— A total of 50 orchid species were assessed (Table 1) using the EECORisk pipeline under IUCN Criterion B. Of these, seven species (14%) were categorized as Critically Endangered (CR), 23 (46%) as Endangered (EN), 14 (28%) as Vulnerable (VU), and six (12%) as Least Concern/Near Threatened (LC/NT) (Fig. 7). All species exhibited continuing decline in habitat [B(b)(iii)], with forest loss ranging from 0.9% to 21.8% around their occurrences. The seven CR species (*Encyclia tuluaensis* J.S.Moreno, Tamayo-Cen & Carnevali, *Epidendrum musciferum* Lindl., *Heterotaxis valenzuelana* (A.Rich.) Ojeda & Carnevali, *Liparis nervosa* (Thunb.) Lindl, *Malaxis histionantha* (Link) Garay & Dunst., *Ornithocephalus gladiatus* Hook., and *Xylobium foveatum* (Lindl.) G.Nicholson) are each known from a single location (1–2 records) with AOO ≤ 8 km² and confirmed ongoing forest loss, meeting CR thresholds under B2ab(iii). *Encyclia parkeri* Reina-Rodr. & Leopardi, although with four records, has an extremely restricted EOO (9.4 km²) and is categorized as EN.

The six species categorized as LC/NT—*Cyrtopodium paniculatum* (Ruiz & Pav.) Garay, *Dimerandra emarginata* (G.Mey.) Hoehne, *Epidendrum melinanthum* Schltr, *Jacquiniella globosa* (Jacq.) Schltr., *Trichocentrum carthagenense* (Jacq.) M.W.Chase, and *Trizeuxis falcata* Lindl.—each had >10 locations and relatively large EOO values. In contrast, *Cattleya quadricolor*, though initially categorized as LC/NT under the standard 10 km threat-grid analysis, is reclassified as VU(B1+B2ab-iii) when the threat grid is adjusted to 20 km to reflect the landscape-scale operation of industrial sugarcane monoculture across the valley floor (EOO = 2,145.1 km², AOO = 88 km², 8 threat-defined locations, 6.4% forest loss).

Discussion. The findings of this study highlight significant conservation concerns for orchid species within the TDF of Valle del Cauca. Of the 50 species assessed, 44 (88%) were categorized in a threat category (CR, EN, or

Table 1. Regional conservation assessment results for 50 orchid species from the Tropical Dry Forest of Valle del Cauca (Colombia) under IUCN Criterion B. For each species we report: Extent of Occurrence (EOO; km²), Area of Occupancy (AOO; km²), number of threat-defined locations, number of subpopulations, whether severe fragmentation was detected [B(a)], whether continuing decline in habitat was detected [B(b)(iii)] with percent forest loss, and the final IUCN category with explicit subcriteria. NA indicates EOO could not be calculated (fewer than 3 occurrence points).

Species	EOO (km²)	AOO (km²)	Locations	Subpop.	Frag. B(a)	Decline B(b)(iii)	% Forest loss	Category	Subcriteria
Acianthera capillaris (Lindl.) Pridgeon & M.W.Chase	533.0	16	4	4	No	Yes	2.5	EN	B1+B2ab(iii)
Bletia purpurea (Lam.) A.DC.	175.4	12	3	3	No	Yes	5.8	EN	B1+B2ab(iii)
Catasetum ochraceum Lindl.	2059.8	36	7	5	No	Yes	10.5	VU	B1+B2ab(iii)
Catasetum tabulare Lindl.	5241.9	28	7	7	No	Yes	3.2	VU	B1+B2ab(iii)
Cattleya quadricolor B.S.Williams	2145.1	88	8	6	No	Yes	6.4	VU	B1+B2ab(iii)
Cyclopogon elatus (Sw.) Schltr.	2379.4	28	7	7	No	Yes	4.1	VU	B1+B2ab(iii)
Cyclopogon lindleyanus (Link, Klotzsch & Otto) Schltr.	602.3	20	5	3	No	Yes	0.9	EN	B1+B2ab(iii)
Cyrtopodium paniculatum (Ruiz & Pav.) Garay	6777.3	68	17	12	No	Yes	4.3	LC/NT	—
Dimerandra emarginata (G.Mey.) Hoehne	10569.5	84	19	15	No	Yes	5.5	LC/NT	—
Encyclia ceratistes (Lindl.) Schltr.	2417.2	20	5	5	No	Yes	3.5	EN	B1+B2ab(iii)
Encyclia parkeri Reina-Rodr. & Leopardi	9.4	12	2	1	No	Yes	21.8	EN	B1+B2ab(iii)
Encyclia tuluaensis J.S.Moreno, Tamayo-Cen & Carnevali	NA	4	1	1	No	Yes	2.7	CR	B2ab(iii)
Epidendrum flexuosum G.Mey.	35.4	8	2	2	No	Yes	2.8	EN	B1+B2ab(iii)
Epidendrum lambeauanum De Wild.	2168.8	40	10	7	No	Yes	4.1	VU	B1+B2ab(iii)
Epidendrum lanipes Lindl.	1499.1	16	4	4	No	Yes	6.3	EN	B1+B2ab(iii)
Epidendrum melinanthum Schltr.	8387.7	108	23	12	No	Yes	6.0	LC/NT	—
Epidendrum musciferum Lindl.	NA	4	1	1	No	Yes	3.5	CR	B2ab(iii)
Epidendrum porquerense F.Lehm. & Kraenzl.	2977.3	28	7	6	No	Yes	6.6	VU	B1+B2ab(iii)
Epidendrum rigidum Jacq.	4417.0	36	8	7	No	Yes	4.6	VU	B1+B2ab(iii)
Epidendrum ruizianum Steud	2485.1	12	3	3	No	Yes	6.9	EN	B1+B2ab(iii)
Eulophia alta (L.) Fawc. & Rendle	27.0	16	2	2	No	Yes	5.8	EN	B1+B2ab(iii)
Eulophia maculata (Lindl.) Rchb.f.	1646.9	24	6	6	No	Yes	4.7	VU	B1+B2ab(iii)
Galeandra beyrichii Rchb.f.	6584.5	40	9	8	No	Yes	3.6	VU	B1+B2ab(iii)

TABLE 1. *continues...*

Heterotaxis equitans (Schltr.) Ojeda & Carnevali	1293.5	20	5	3	No	Yes	5.1	EN	B1+B2ab(iii)
Heterotaxis valenzuelana (A.Rich.) Ojeda & Carnevali	NA	4	1	1	No	Yes	4.2	CR	B2ab(iii)
Jacquiniella globosa (Jacq.) Schltr.	3612.8	52	13	11	No	Yes	5.7	LC/NT	—
Laelia splendida (Schltr.) L.O.Williams	NA	8	2	2	No	Yes	9.7	EN	B2ab(iii)
Liparis nervosa (Thunb.) Lindl.	NA	4	1	1	No	Yes	8.3	CR	B2ab(iii)
Malaxis histionantha (Link) Garay & Dunst.	NA	4	1	1	No	Yes	1.5	CR	B2ab(iii)
Maxillariella guareimensis (Rchb.f.) M.A.Blanco & Carnevali	329.5	20	5	5	No	Yes	4.8	EN	B1+B2ab(iii)
Mormolyca tenuibulba (Christenson) M.A.Blanco	12.3	12	3	2	No	Yes	6.0	EN	B1+B2ab(iii)
Nemaconia striata (Lindl.) Van den Berg, Salazar & Soto Arenas	981.3	16	4	4	No	Yes	5.2	EN	B1+B2ab(iii)
Notylia sagittifera (Kunth) Link, Klotzsch & Otto	986.2	16	4	4	No	Yes	4.6	EN	B1+B2ab(iii)
Oncidium pictum Kunth	855.5	24	5	5	No	Yes	4.7	EN	B1+B2ab(iii)
Ornithocephalus gladiatus Hook.	NA	8	1	1	No	Yes	3.8	CR	B2ab(iii)
Pabstiella aryter (Luer) F.Barros	NA	8	2	2	No	Yes	3.3	EN	B2ab(iii)
Pelexia olivacea Rolfe	2971.8	32	8	7	No	Yes	6.4	VU	B1+B2ab(iii)
Polystachya foliosa (Hook.) Rchb.f.	3007.6	20	5	4	No	Yes	4.9	EN	B1+B2ab(iii)
Prosthechea livida (Lindl.) W.E.Higgins	1023.8	20	5	4	No	Yes	5.0	EN	B1+B2ab(iii)
Rhetinantha friedrichsthalii (Rchb.f.) M.A.Blanco	1259.4	28	7	6	No	Yes	4.4	VU	B1+B2ab(iii)
Rodriguezia granadensis (Lindl.) Rchb.f.	577.0	16	4	3	No	Yes	2.3	EN	B1+B2ab(iii)
Rodriguezia lanceolata Ruiz & Pav.	1133.9	20	5	5	No	Yes	5.4	EN	B1+B2ab(iii)
Scaphyglottis prolifera (R.Br.) Cogn.	3303.5	40	9	8	No	Yes	6.8	VU	B1+B2ab(iii)
Sobralia densifoliata Schltr.	NA	8	2	2	No	Yes	5.0	EN	B2ab(iii)
Sobralia roezlii Rchb.f.	541.5	16	4	4	No	Yes	4.3	EN	B1+B2ab(iii)
Trichocentrum carthagenense (Jacq.) M.W.Chase & N.H.Williams	7488.2	72	17	14	No	Yes	5.3	LC/NT	—
Trizeuxis falcata Lindl.	3045.7	56	13	8	No	Yes	5.7	LC/NT	—
Vanilla calyculata Schltr.	1305.8	44	10	8	No	Yes	4.7	VU	B1+B2ab(iii)
Vanilla odorata C. Presl.	3105.5	32	7	7	No	Yes	5.8	VU	B1+B2ab(iii)
Xylobium foveatum (Lindl.) G.Nicholson	NA	4	1	1	No	Yes	3.5	CR	B2ab(iii)

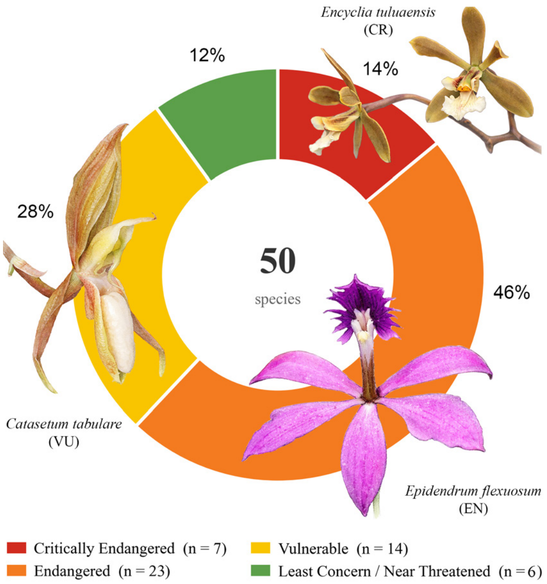

FIGURE 7. Conservation status of orchid species assessed in this study, based on IUCN Criterion B. Figure prepared by J.S. Moreno

VU) under IUCN Criterion B, and continuing habitat decline was confirmed for all species through the Hansen GFC analysis. These results reflect the extreme fragmentation and ongoing degradation of TDF remnants in the region, where less than 8% of the original forest cover remains (Pizano & García, 2014). Importantly, such spatial configurations heighten the risk of local extinction (extirpation); species that may not be globally threatened can nonetheless disappear from specific remnants when isolation reduces demographic rescue and constrains reproduction and recruitment (Tremblay & Ackerman, 2001; Swarts & Dixon, 2009). These processes help explain why regional conservation priorities must emphasize not only protecting remaining fragments but also restoring connectivity through corridors and habitat recovery (Crain & White, 2011; Reina-Rodríguez *et al*., 2016).

It is important to note that although some previous studies reported higher orchid diversity in the region, they often included larger geographic areas encompassing multiple departments, such as Valle del Cauca, Risaralda, Cauca, and Quindío, all part of the Geographical Valley of the Cauca River. For example, Reina-Rodríguez (2016) documented 71 species in the Geographical Valley of the Cauca River. This may be explained by the fact that studies covering multiple sites often inherently include a broader range of habitats and microclimatic conditions (Kolanowska, 2014). Conversely, Ramos and Silverstone (2018) recorded 36 orchid species across this broader geographic area. In comparison, our study, which focused solely on Valle del Cauca, recorded 50 species. Distinguishing differences in scale among the studies is crucial for interpreting the conservation needs of orchids within the TDF of Valle del Cauca and underscores the significance of finer geographic scales in revealing locally relevant patterns of orchid diversity that broader regional assessments may overlook.

Sampling structure and institutional data concentration.— Patterns in records and richness should be interpreted considering the historical and institutional structure of botanical collecting in Valle del Cauca. The dominance of CUVC records reflects the sustained activity of this herbarium in the region. Municipality-level richness rankings (Zarzal, Buga, Tuluá) are concordant with previous inventories (Reina-Rodríguez, 2016) and likely reflect both biological patterns and heterogeneous sampling effort; more standardized surveys across other TDF remnants could reveal additional taxa at those localities.

Mid-elevation zones and their ecological role.— The peak in orchid richness between 900 and 1300 m a.s.l. is consistent with mid-elevation diversity hotspots documented for orchids in other tropical regions, including New Guinea (Schuiteman & de Vogel, 2007) and Costa Rica (Crain & Fernández, 2020). These elevational zones integrate favorable microclimatic conditions—moderate temperatures, higher humidity, and reduced drought stress—that support epiphytic orchid communities even in seasonally dry landscapes (Crain & Tremblay, 2017). Reina-Rodríguez *et al*. (2016) identified mid-elevation areas in Valle del Cauca as potential climatic refugia for dry forest orchids under future scenarios and proposed the implementation of altitudinal migration corridors (AMCs) to connect lowland forest remnants with more stable mid-elevation habitats. Initiatives such as the Yaguarundi Corridor (Hernández, 2021), which aim to restore connectivity across the Geographical Valley of the Cauca River, are essential for maintaining these elevational gradients and the ecological processes they support.

Historical context of the Tropical Dry Forest.— The extreme fragmentation detected in our analyses has deep historical roots. The TDF of Valle del Cauca has undergone intensive transformation since the late 19th century, driven primarily by sugarcane expansion, cattle ranching, and urbanization (Giraldo Díaz, 2010; Uribe-Castro, 2015; Montano Fuentes *et al*., 2022). Large-scale land transformation drastically reduced and subdivided dry-forest cover, with estimates suggesting that major losses accumulated rapidly between 1870 and 1950 and that only a small fraction of the original ecosystem remains today (Giraldo Díaz, 2010). This legacy of conversion helps explain why many orchid taxa now persist as small, spatially discontinuous populations embedded within an intensive agricultural matrix: once-continuous habitat has become several ecological "islands" where dispersal, recolonization, and demographic rescue are constrained (Haddad *et al*., 2015; Soto-Medina *et al*., 2023). In this context, management actions that stabilize habitat quality within the remaining remnants are essential, alongside broader landscape-scale restoration efforts (Niessen & Calderón, 2002).

Restoration challenges and climate-driven range shifts.— Ecological restoration of the TDF presents unique challenges due to the inherently limited water availability characteristic of the ecosystem, a condition further exacerbated by climate change. Changes in temperature and precipitation have been shown to shift the elevational distribution of species, potentially resulting in the loss of suitable habitats for orchids in the lowlands where they currently thrive (Feeley & Silman, 2010; Lutz *et al*., 2013). Additionally, habitat fragmentation and loss of connectivity between TDF remnants diminish the resilience of these species, limiting their ability to adapt and survive in a rapidly changing environment (González-M. *et al*., 2018; Haddad *et al*., 2015). New approaches to restoration emphasize the importance of socio-ecological monitoring platforms that integrate local communities and adaptive management strategies (Norden *et al*., 2021).

Importance of Hacienda El Medio.— The prominence of Hacienda El Medio in our dataset reinforces its relevance as a key locality for orchid diversity within the tropical dry forest of Valle del Cauca. This pattern is consistent with prior intensive inventories in the area (Ramos & Silverstone, 2018; Reina-Rodríguez, 2016). Importantly, this consistency strengthens confidence in Zarzal/El Medio as a persistent diversity nucleus, while also highlighting a broader conservation message: high recorded richness can coexist with severe fragmentation and isolation, underscoring the need for site-based protection coupled with landscape-scale connectivity measures. The ecological value of El Medio is further supported by historical descriptions indicating that former cacao plantations transitioned into secondary forests dominated by native canopy trees such as *Anacardium excelsum* (Bertero & Balb. ex Kunth) Skeels, generating structurally complex habitats that function as refugia for orchids and other epiphytes (Ramos & Silverstone, 2018). Together, the convergence of historical and contemporary evidence emphasizes that remnant mid-elevation habitats, such as those in Hacienda El Medio, are disproportionately important for maintaining orchid diversity in the Cauca Valley and therefore merit priority attention within regional conservation and restoration strategies.

Data Deficiency reassessment.— Nine species in our dataset are known from a single locality (1–2 records), yielding AOO ≤ 8 km² and EOO not calculable (<3 points). The EECORisk pipeline enabled formal categorization of these species under B2 by evaluating B(b)(iii) habitat decline via Hansen GFC data, even for single-locality occurrences. Of these, seven species are categorized as CR under B2ab(iii) (e.g., *Liparis nervosa*: 1 location, AOO = 4 km², 8.3% forest loss; *Xylobium foveatum*: 1 location, AOO = 4 km², 3.5% forest loss), and two are categorized as EN under B2ab(iii) (*Laelia splendida* (Schltr.) L.O.Williams, *Sobralia densifoliata* Schltr.). Nonetheless, targeted field expeditions to historically documented localities and nearby suitable remnants remain essential to verify persistence, assess habitat condition, and obtain population metrics for these poorly known species.

Ongoing discovery and the role of protected areas and local institutions.— A key implication of working in highly fragmented TDF landscapes is that orchid diversity can remain underestimated even at relatively local scales. The recent description of *Encyclia tuluaensis* (Moreno *et al*., 2024) (Fig. 8) from

Figure 8. *Encyclia tuluaensis*, recently discovered in the Juan María Céspedes Botanical Garden (Tuluá), representing ongoing taxonomic discoveries in fragmented tropical dry forests. Despite decades of surveys, this endemic species remained undiscovered until recent fieldwork. Categorized as Critically Endangered (CR; AOO = 4 km², single location), its discovery was translated into local conservation action: declared municipal flower of Tuluá through collaboration between botanical institutions and local government. Photograph by J.S. Moreno.

the Juan María Céspedes Botanical Garden (Tuluá), here categorized as CR(B2ab(iii)) with AOO = 4 km² and a single known location, illustrates the ongoing potential for taxonomic discoveries that immediately qualify as critically threatened. Importantly, the subsequent declaration of *E. tuluaensis* as the municipal flower of Tuluá—promoted through local leadership involving the botanical gardens (including Cali and Juan María Céspedes Botanical Gardens) and the Municipal Council—shows how scientific discovery can be translated into cultural identity and civic recognition, strengthening social appropriation, environmental education, and political momentum for local conservation action. This underscores that site-based conservation (e.g., private reserves, riparian buffers, and botanical institutions) is not only relevant for safeguarding known populations but can also reveal previously unrecognized endemic diversity.

Focal species.— *Cattleya quadricolor* (Fig. 9) presents an instructive case of divergence between formal Criterion B assessment and regional conservation concern. Under our EECORisk analysis with a standard 10 km threat grid, this species yielded 14 locations and was categorized as LC/NT. However, in Valle del Cauca, the dominant threat—industrial sugarcane monoculture—operates at a landscape scale that exceeds the standard 10 km cell, uniformly affecting all remnants across the valley floor. When the threat grid is adjusted to 20 km to reflect this spatially correlated threat, the number of locations decreases to 8, and the species is categorized as VU(B1+B2ab(iii)), with an EOO of 2145.1 km², an AOO of 88 km², and 6.4% continuing forest loss around occurrences. This adjusted categorization is more consistent with other evidence: Resolution 0126 (Ministerio de Ambiente y Desarrollo Sostenible, 2024) classifies the species nationally as

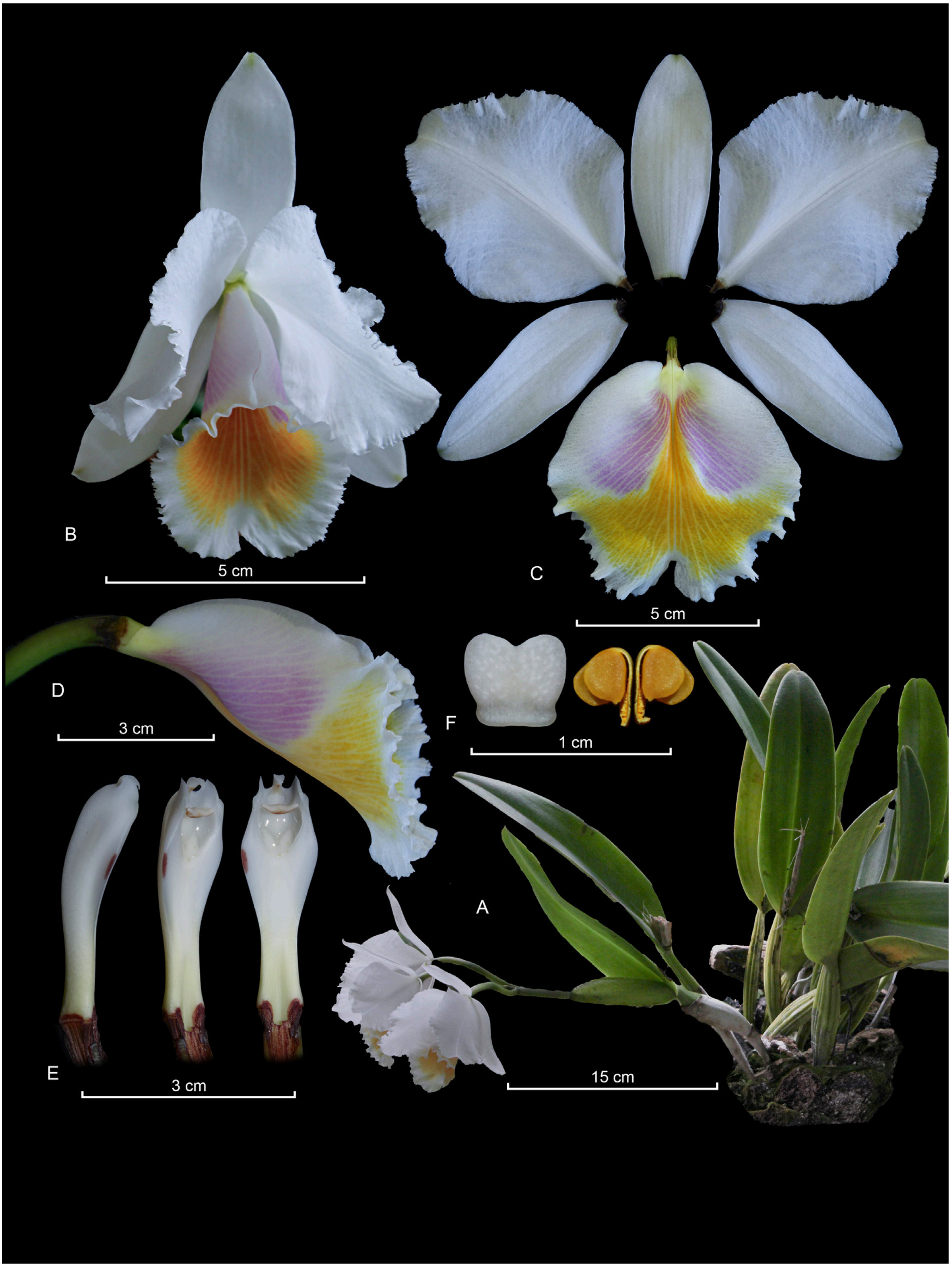

Figure 9. Lankester Composite Digital Plate (LCDP) of *Cattleya quadricolor*. **A**. Habit. **B**. Flower. **C**. Dissected perianth. **D**. Ovary, column, and lip, lateral view. **E**. Column, lateral, ¾, and ventral views. **F**. Anther cap and pollinarium. LCDP by J.S. Moreno.

Endangered under criteria not evaluated here (population decline, overexploitation), and the Management Plan for the Conservation of 22 Focal Plant Species in Valle del Cauca classified it as Critically Endangered under criterion A2cd (CVC, 2011; Reina-Rodríguez, 2012). The species' 6 subpopulations are embedded in a landscape where >92% of TDF has been converted, and the ongoing forest loss indicates that habitat quality continues to deteriorate. This case illustrates that Criterion B assessments based on geographic range metrics alone may underestimate threat levels for species facing spatially correlated, landscape-scale pressures, and that the definition of "location" sensu IUCN must carefully consider the spatial grain of the most plausible threat. Furthermore, the conservation of *Cattleya quadricolor* is not only vital because of its intrinsic ecological significance but also because it serves as a representative umbrella species for broader conservation efforts aimed at safeguarding the remaining fragments of the Inter-Andean Tropical Dry Forest.

In this context, botanical gardens play a pivotal role in the *ex situ* conservation of *Cattleya quadricolor* and other threatened orchids, as outlined in the management pathways proposed in this study. The Cali Botanical Garden has led initiatives in the propagation and conservation of native orchid species, including in vitro propagation of *C. quadricolor*, offering a practical avenue for future reintroduction and population reinforcement efforts. Beyond propagation, botanical gardens serve as hubs for research, conservation planning, and environmental education, contributing significantly to the maintenance of genetic diversity. Strengthening collaboration among botanical institutions, universities, and conservation organizations is essential to implement integrated strategies that bridge *in situ* and *ex situ* efforts and enhance the long-term viability of focal species.

Small, fragmented orchid populations face elevated risks of demographic stochasticity and genetic erosion, as documented for *Lepanthes caritensis* Tremblay & Ackerman in Puerto Rico, where a rare endemic survives in only two fragmented forest patches (Crain & Tremblay, 2012). Similar dynamics likely apply to the CR and EN species identified in our study, reinforcing the urgency of both habitat protection and population-level monitoring.

Conclusion. This study demonstrates the utility of the EECORisk pipeline (Arango & López-Gallego, 2023; López-Gallego *et al*., 2024) for transparent, reproducible regional conservation assessments of orchids in highly fragmented landscapes. By integrating automated calculation of IUCN Criterion B metrics with satellite-derived habitat analysis (Hansen GFC), the pipeline enables the formal evaluation of subcriteria—including severe fragmentation B(a) and continuing decline B(b)(iii)—that are often assessed only qualitatively or omitted in regional studies. The application of this framework to 50 orchid species in the TDF of Valle del Cauca revealed that 88% of species qualify for a threat category at the departmental scale, and all species show ongoing habitat loss. These findings underscore the urgency of conservation actions: prioritizing habitat protection of remaining TDF remnants, restoring ecological connectivity between fragments—including altitudinal migration corridors linking lowland and mid-elevation habitats—and implementing targeted monitoring programs for the most critically threatened species, including the seven CR species known from single localities. The methodological approach presented here is directly transferable to other taxonomic groups and fragmented ecosystems where regional conservation assessments are needed to inform locally actionable management decisions.

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Author contribution. J.S.M. conceived the study, designed the methodology, conducted field surveys, processed and analyzed all data, created visualizations, and wrote the original manuscript. A.Z. contributed to methodological framework development, data interpretation, and manuscript revision. C.L. provided critical input on tropical dry forest ecology and context and contributed to manuscript writing and revision. All authors reviewed and approved the final version of the manuscript.

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Conflict of interest. The authors declare that they have no conflicts of interest.

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Supporting Information: Additional material related to this article is available in the online Supporting Information section.

Supplementary Table S1. Occurrence records of orchids (Orchidaceae) from the Tropical Dry Forest of Valle del Cauca, Colombia, used in this study (n = 391 records; 50 species across 34 genera). The source/reference column identifies the origin of each record; “Observ.” denotes observations without herbarium vouchers. The abbreviation “s.n.” (*sine numero*) indicates records without an assigned collection number. Place names are given in Spanish as proper toponyms.