Floral phenology of an Andean bellflower and pollination by Buff-tailed Sicklebill hummingbird

**Author Names**: Mannfred M.A. Boehm, David Guevara-Apaza, Jill E. Jankowski, Quentin C.B. Cronk

**Corresponding Author**: [mannfred.boehm@ubc.ca](mailto:mannfred.boehm@ubc.ca)

**Author affiliations**: Department of Botany, University of British Columbia, 3156–6270 University Boulevard, Vancouver, BC, Canada, V6T 1Z4.

Biodiversity Research Centre, University of British Columbia, 2212 Main Mall, Vancouver, BC, Canada, V6T 1Z4.

Facultad de Ciencias Biológicas, Universidad San Antonio Abad del Cusco, Av. de La Cultura 773, Cusco 08000, Peru.

Department of Zoology, University of British Columbia, 4200–6270 University Boulevard, Vancouver, BC, Canada, V6T 1Z4.

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#### Abstract

The Andean bellflowers comprise an explosive radiation correlated with shifts to specialized pollination. One diverse clade has evolved with extremely curved floral tubes and are predicted to be pollinated exclusively by one of two parapatric species of Sicklebill hummingbirds (*Eutoxeres*). In this study we focused on the floral biology of *Centropogon granulosus*, a bellflower thought to be specialized for pollination by *E. condamini*, in a montane cloud forest site in southeastern Peru. Using camera traps and a pollination exclusion experiment, we documented *E. condamini* as the sole pollinator of *C.granulosus*. Visitation by *E. condamini* was necessary for fruit development. Flowering rates were unequivocally linear and conformed to the ‘steady state’ phenological type. Over the course of >1800 hours of monitoring we recorded 12 *E. condamini* visits totaling 42 seconds, indicating traplining behaviour. As predicted by its curved flowers, *C. granulosus* is exclusively pollinated by Buff-tailed Sicklebill within our study area. We present evidence for the congruence of phenology and visitation as a driver of specialization in this highly diverse clade of Andean bellflowers.

#### Introduction

The Andean bellflowers (Lobelioideae) of *Centropogon*, *Siphocampylus*, and *Burmeistera* (the ‘centropogonids’) comprise over 550 species emerging in the last five million years ([Lagomarsino *et al.* 2016](#ref-lagomarsino_2016)). This rapid diversification is correlated, in part, with the repeated evolution of pollination by bats and hummingbirds ([Lagomarsino *et al.* 2017](#ref-lagomarsino_2017)). For some centropogonids, pollinator shifts are concomitant with pollinator specialization which can initiate or reinforce reproductive isolation ([Lagomarsino & Muchhala 2019](#ref-lagomarsino_2019)). That is, a pollinator shift may incidentally reduce the number of effective pollinators and in some cases lower interspecific pollen transfer ([Armbruster 2017](#ref-armbruster_2017)). Although it is unknown whether specialization is a cause or consequence of rapid radiations, they are likely to play a role in the maintenance of diversity in this species-rich clade ([Kay & Sargent 2009](#ref-kay_2009); [Armbruster 2014](#ref-armbruster_2014)).

   One diverse clade of *Centropogon*, the ‘eucentropogonids’ (38 spp.), evolved after a single unique shift to pollination by Sicklebill hummingbirds (*Eutoxeres*, [Lagomarsino *et al.* 2017](#ref-lagomarsino_2017)). Almost all members of this clade are predicted, on the basis of their strongly curved corolla tubes, to be pollinated by Sicklebills ([Stein 1987](#ref-stein_1987)). In this study we focus on the pollination of *Centropogon granulosus* C.Presl by Buff-tailed Sicklebill (*Eutoxeres condamini*).

*C. granulosus* is an understory vine with abruptly curved, bright red to orange tubular flowers (Figure 1). This species is both the most widespread and variable eucentropogonid, occurring from southern Nicaragua to Bolivia. The species examined here conforms to *Centropogon granulosus* subsp. *granulosus* (sensu [Stein 1987](#ref-stein_1987)). Although other eucentropogonid species are found in this region ([Stein 1987](#ref-stein_1987)), we focus on *C. granulosus* as it has been previously studied in Costa Rica with respect to pollination by another Sicklebill species, *Eutoxeres aquila* ([Stiles 1985](#ref-stiles_1985)), the only congener of *E. condamini*. Moreover, *C. granulosus* is locally abundant, providing a tractable system for study.

*Eutoxeres* is comprised of two parapatric species of Sicklebill hummingbirds, that together, adhere to the geographic distribution of the eucentropogonids ([Abrahamczyk *et al.* 2017](#ref-abrahamczyk_2017)). White-tipped Sicklebill (*Eutoxeres aquila*) occurs from Costa Rica to northern Peru, while Buff-tailed Sicklebill (*E. condamini*) occurs from northern Peru to Bolivia (Hinkelmann & Boesman 2020). Previous studies have supported White-tipped Sicklebill as a specialized pollinator of eucentropogonids and some *Heliconia* spp. with curved corolla tubes ([Stiles 1985](#ref-stiles_1985); [Gill 1987](#ref-gill_1987); [Maglianesi *et al.* 2015](#ref-maglianesi_2015); [Morrison & Mendenhall 2020](#ref-morrison_2020)). Its bill curvature matches the curved corollas of these plants more than other co-occurring Hermits ([Maglianesi *et al.* 2014](#ref-maglianesi_2014); [Sonne *et al.* 2019](#ref-sonne_2019)). Further, its local abundance is correlated with seasonal flowering of *C. granulosus* in Costa Rica ([Stiles 1985](#ref-stiles_1985)). In contrast, very little is known of its southern congener, *E. condamini*. Like *E. aquila*, its curved bill appears to be suited to feed from eucentropogonids. Currently, there is only a single written record of visitation to a eucentropogonid (*Centropogon gamosepalus* Zahlbr., [Stein 1987](#ref-stein_1987)), and further details on the extent of mutualism have not yet been studied (e.g. effects of visitation on fruit set and seed production).

   Furthermore, because this pollination system is thought to be specialized, we expect additional aspects of the pollination syndrome, specifically phenology, to reflect adaptation to *Eutoxeres* behaviour. In addition to the seasonal flowering trends documented by Stiles ([1985](#ref-stiles_1985)), phenological patterns at finer temporal scales (i.e. days) might also conform to the daily foraging habits of *Eutoxeres*. Phenological patterns at this scale have been previously categorized by Gentry ([1974](#ref-gentry_1974)): for example, ‘big bang’ species produce many flowers simultaneously over several days, while ‘steady state’ species produce only a few flowers per day over a number of weeks. Considering that *E. aquila* is a trapliner ([Stiles 1985](#ref-stiles_1985); but see [Sargent *et al.* 2021](#ref-sargent_2021)), the ‘phenological type’ of Gentry ([1974](#ref-gentry_1974)) that eucentropogonids are likely to exhibit is steady state flowering, consistent with low, but regular, daily visitation rates by pollinators. Moreover, we expect steady state flowering to provide insufficient daily nectar to territorial hummingbirds so that these plants would therefore only be visited by traplining species ([Kessler *et al.* 2020](#ref-kessler_2020)).

   Although the phenological types of some centropogonids have been described qualitatively, (e.g. [Colwell *et al.* 1974](#ref-colwell_1974); [Weiss 1996](#ref-weiss_1996)), the ‘phenological type’ framework of Gentry ([1974](#ref-gentry_1974)) considers two continuous variables, flowering duration () and rate (). We propose that to categorize phenological types, the anthesis rate () should be examined for linearity, where we expect steady state species to exhibit a constant daily flowering rate, whereas ‘cornucopia’ and ‘big bang’ species would flower non-linearly ([Gentry 1974](#ref-gentry_1974)). To this end, the *average deviation from linearity* metric ([Kroll *et al.* 2000](#ref-kroll_2000)) will be useful in developing a reproducible, quantitative framework for assigning Gentry’s ([1974](#ref-gentry_1974)) phenological types (see: Methods).

   The goal of this study is to test the hypothesis that eucentropogonids are uniquely specialized for pollination by Sicklebill hummingbirds, specifically the less well-known Buff-tailed Sicklebill, by examining the floral phenology and pollination of *Centropogon granulosus*. Specifically, we ask: (1) Is Buff-tailed Sicklebill a visitor to, and the sole pollinator of *C. granulosus*? (2) Does Sicklebill visitation affect the reproductive success of *C. granulosus*? and (3) Is the phenological type of *C. granulosus* consistent with adaptation to the presumed foraging mode of Buff-tailed Sicklebill, i.e. does *C. granulosus* exhibit steady state flowering?

#### Materials and Methods

***Field Site***—

   We based our field work at the Cock-of-the-Rock Lodge situated at ~1350 m a.s.l. in the Kosñipata Valley, Department of Cusco, Peru (-13.055, -71.548 DD). Research Permit #0441-2017 was administered by the Servicio Nacional Forestal y de Fauna Silvestre (SERFOR). The field site is stationed at the transition of lower montane forest and cloud forest within the Yungas ecoregion on the eastern slope of the Peruvian Andes (Figure 2). Local mean annual rainfall and temperature is 2631 mm and 19.1 °C, respectively ([Salinas *et al.* 2011](#ref-salinas_2011)).

***Pollinator Observations***—

   We deployed five camera traps (Hyperfire HC600, Reconyx Inc.) near *Centropogon granulosus* vines located in a previous survey of the area ([Boehm *et al.* 2018](#ref-boehm_2018a)). Cameras were mounted onto nearby trees using bungee cord, typically at a distance of 1-2 meters from (and at a height equivalent to) the inflorescence. Camera traps were checked for new captures every 12 hours. If no floral visitors were recorded within three days, the camera traps were moved to different *C. granulosus* individuals. Where floral visitors were recorded, we attempted targeted video recording to better document visitation behaviour. Camera traps were active continuously from August 17 to September 20, 2017 (Table A1).

***Pollinator exclusion and floral development***—

   Following the methods of Sun et al. ([2017](#ref-sun_2017)), we constructed and deployed wire cages covering one inflorescence each from six *Centropogon* individuals (Figure A3). Wire cages prevent hummingbirds from accessing the flowers while allowing invertebrates to move freely. An additional ten inflorescences (one per individual plant) were marked with cardstock tags tied to the stem and monitored as controls. Using the control flowers, we defined eight stages of floral development (A-H; Table A2, Figure 4). These stages were used to quantify and compare the developmental trajectories of the control and pollinator-excluded flowers. Monitoring of a flower stopped when (1) berry development completed (stage H), (2) the flower died prematurely, or (3) the study period ended. Daily observations were recorded between August 17 and September 20, 2017. Floral development data were analysed in R v.4.0.2 ([R Core Team 2017](#ref-R_2017)).

   Some flowering stages were not completely observed due to herbivory or weather. Similarly, monitoring of some flowers began with the current stage partially completed. This type of data is ‘right censored’, i.e. the true durations of these stages are greater than was observed ([Allison 2014](#ref-allison_2014)). To account for censoring, we fit parametric survival functions ([Allison 2014](#ref-allison_2014)) to the stage duration data. This allowed an estimation of the median duration () for each stage (), i.e. the number of days elapsed in stage before the daily probability of transitioning to stage surpassed 50%. Survival functions and median stage durations were estimated from the Gompertz distribution ([Ricklefs & Scheuerlein 2002](#ref-ricklefs_2002)) using flexsurv v.2.0 ([Jackson 2016](#ref-jackson_2016)).

   To reconstruct floral development from the censored dataset, we used the median stage durations and 95% confidence intervals (CI) estimated from the survival analysis above. For each treatment, we cumulatively summed the median stage durations to approximate the number of days elapsed between stages A and G. We accounted for error propagation, i.e. the uncertainty of each in influencing the 95% CI of , by summing the 95% CIs in quadrature ([Ku 1966](#ref-ku_1966)).

***Phenological type***—

   To characterize the phenological type of *C. granulosus*, we used broom v.0.7.6 ([Robinson *et al.* 2021](#ref-robinson_2021)) to fit linear models to the number of flowers produced through time. A separate model was fit for each inflorescence that produced at least five flowers ( = 5 for each treatment). The slope of each linear regression was interpreted as the anthesis rate. To assess linearity, we used lin.eval v.0.1.2 ([Shrivastav 2019](#ref-shrivastav_2019)) to fit linear and polynomial (>1) curves to the anthesis rate. This method uses the *average deviation from linearity* ([Kroll *et al.* 2000](#ref-kroll_2000)), to determine if non-linear fits have significantly lower residuals than a linear regression.

#### Results

***Floral Visitors***—

Camera trap recordings and *in situ* observations confirm Buff-tailed Sicklebill (*E. condamini*) as a visitor to *Centropogon granulosus* flowers (Figs. 3 and A4). Visitation tended to occur from 5:20 to 10:40 in the morning (=9), and 12:40 to 16:30 in the afternoon (=3), though these patterns may have been affected by our activity in the area. Given that *Eutoxeres* is active within an ~11-hour daily window, the total monitoring effort was ~1870 hours (5 camera traps 34 days 11 hours per day). Within this time we recorded 12 visits to six *C. granulosus* individuals, totaling 42 seconds of *E. condamini* observation (Figure A12, Table A3). Ten of the 12 records were single, brief visits (≤3 seconds) that occurred once in the day — two additional records were made when a second visitation was observed on the same day. A total of seven flowers were probed from six *C. granulosus* individuals, i.e. a second visit was recorded to an inflorescence as flowers opened sequentially. *E condamini* feeds both by perching on the lignified inflorescence (=3), as well as hovering (=9). We also recorded two instances of Sicklebills approaching and inspecting inflorescences without open flowers. Wedge-billed hummingbird (*Schistes geoffroyi*) was also recorded nectar robbing *C. granulosus* by piercing the corolla tube at the base. Over the course of two days, a camera trap recorded five visits per day to the same inflorescence (Table A4). Further details of *S. geoffroyi* behaviour can be found in Boehm ([2018](#ref-boehm_2018b)). No other hummingbirds were recorded visiting these flowers.

   Reviewing still frames from the video recording reveals an interesting feeding problem posed by the sharply curved flowers of *C. granulosus*. The hook shape forces the hummingbird to hover below the corolla opening and tilt its head backwards so that it is facing skyward (dorsal head flexion), at which point it can insert the tip of its bill into the flower aperture (Figure A4). The remainder of the bill is further inserted by tilting the head back to a forward-facing position while lifting itself to eye level with the corolla opening. Due to the unique morphology and orientation of *C. granulosus* flowers, this hovering maneuver is likely performed only by *Eutoxeres*. We note that once the bill is inserted, the throat and crown are covered by the ventral and dorsal corolla lobes, respectively.

   Two additional vertebrates, a murid (Muridae) and a long-nosed bat (Glossophaginae) were recorded near the inflorescences, but not observed to interact with the plant directly (Figs. S5, S6). We note this because it is unknown how the fleshy berries are dispersed, though we documented signs of frugivory (Figure A7).

   Numerous invertebrates occupied or visited the flowers of *C. granulosus* in this study. As found in previous studies, we observed ants ([Stein 1992](#ref-stein_1992)), mites ([Naskrecki & Colwell 1998](#ref-naskrecki_1998)), and dipterids ([Weiss 1996](#ref-weiss_1996)) in or on the flowers of this species. We observed unidentified Aranids inside of the floral tubes, and note that *Anelosimus* spiders (Araneae) are known to build webs scaffolded by *Centropogon coccineus* (Hook.) Regel ex B.D.Jacks. ([Nentwig & Christenson 1986](#ref-nentwig_1986)). We also recorded a larval lepidopteran inhabiting a flower (Figure A8), and a stingless bee (Meliponini) collecting pollen from the anther scale (Figure A9).

***Pollinator exclusion and floral development***—

   We identified and described eight stages of floral development in *C. granulosus* (Table A2, Figure 4). During the first stage (A), the flowers are small buds, and have not yet developed curvature. In stages B to D, the flowers elongate and form their characteristic hook shape — nearly all floral curvature is developed here. Stages E and F are defined by the staminate and pistillate phases of anthesis, respectively. Following anthesis, the flowers wilt (Stage G) and produce berries (Stage H, Table A2).

   These eight stages were used to compare developmental differences between control and pollinator-excluded flowers (Figure 4). Between treatments, the progression of floral development is comparable from stages A (bud development) to E (anthesis). However, control flowers spend 24.2 ± 4.47 days (median ± 95% CI) developing berries, while no hummingbird-excluded flowers produced berries.

***Flowering rate***—

   Hummingbird exclusion did not affect the total number of flowers produced (=0.782, =0.282, =0.15). The caged inflorescences produced 11.2 ± 4.6 flowers over the study period (34 days), whereas controls produced 12.2 ± 8.1 flowers (mean ± SE). The upper limit of flower production for a single inflorescence has not been determined, though we counted 68 flower abscission scars on the peduncle of an individual not included in this study (Figure A10).

   Linear models accurately described flowering rate (Figure 5): all anthesis rates were fit better by linear models than polynomials ( < 0.05). Flowering rate (slope) varied among inflorescences (=0.027, =2.70, =1.91), but not between treatments (=0.200, =1.40, =0.99). The average rate was one anthesis event per 3.23 ± 0.12 days for control inflorescences and 4.60 ± 0.07 days for pollinator-excluded inflorescences. The highest flowering rate was documented in a control plant at 1.88 days, nearly twice the rate of the next fastest individual (Figure 5). When the fast inflorescence is removed, the mean flowering rate for control plants is 3.94 ± 0.03 days. The lowest flowering rates were 7.22 days and 7.06 days, both in pollinator-excluded plants.

#### Discussion

***Buff-tailed Sicklebill is a pollinator of*** **C. granulosus**—

As predicted from its extreme bill curvature, Buff-tailed Sicklebill (*E. condamini*) is a visitor to *C. granulosus*, and these visits are necessary for developing fruit. No other hummingbirds were observed legitimately probing these flowers. Covering flowers with wire cages excluded hummingbirds while allowing invertebrates to access the flowers freely — however none of these flowers produced fruits. Therefore, we conclude that Buff-tailed Sicklebill is the sole pollinator of *C. granulosus*.

   While probing for nectar, the face of *E. condamini* is inserted into the corolla tube so that the crown and throat are covered by the petal lobes. This is facilitated by the exceptionally inflated corolla opening characteristic of the eucentropogonids ([Lagomarsino *et al.* 2017](#ref-lagomarsino_2017)). While narrow corolla apertures are thought to promote specialization ([Temeles *et al.* 2002](#ref-temeles_2002)), the evolution of curvature might relax selection for corolla width. Conversely, because *E. condamini* tilts its head backwards during bill insertion, it may not be able to see the corolla opening; thus, a narrow corolla width could negatively affect pollination if the barriers to accessing nectar are too high ([Westerkamp 1990](#ref-westerkamp_1990); [Rico-Guevara *et al.* 2021](#ref-ricoguevara_2021)).

   In contrast to previous accounts of Sicklebill visitation to *Centropogon* ([Stiles 1985](#ref-stiles_1985); [Stein 1987](#ref-stein_1987)), we observed hovering in addition to perching. While floral orientation in some hummingbird-pollinated plants may have evolved to exclude non-hovering visitors (R. Colwell, *pers. comm.*), hovering is one of the most energetically expensive modes of locomotion ([Suarez & Gass 2002](#ref-suarez_2002)) and is avoided when perches are available ([Westerkamp 1990](#ref-westerkamp_1990)). Recent work has found that short-billed hummingbird species have repeatedly evolved large claws that improve their ability to perch (R. Colwell, *pers. comm.*). Conversely, long-billed species tend to hover to feed, supporting the idea that long (and sometimes curved) tubular flowers evolve in response to selection for pollinator specialization ([Temeles *et al.* 2019](#ref-temeles_2019)). We speculate that the inflorescences of *C. granulosus* are lignified primarily to support and orient flowers, and are only opportunistically used by Sicklebills as perches. This is because open flowers tend to face away from the stem on long pedicels (Figure 2). This is in contrast to *E. condamini* visits to nearby *Heliconia*, which has flowers oriented so that the aperture is aligned with the perch (i.e. floral bract, Figure A11). Whether floral orientation promotes specialization in the eucentropogonids is an understudied aspect of pollination in this clade.

***Steady State Flowering and Traplining***—

Because hummingbird species generally adhere to a single foraging mode ([Feinsinger & Colwell 1978](#ref-feinsinger_1978); [Stiles 1985](#ref-stiles_1985); but see [Sargent *et al.* 2021](#ref-sargent_2021)), phenological types may be effective filters of the local pollinator community, further promoting floral specialization in the eucentropogonids. As with floral shape, phenological types are thought to evolve either via competition for pollination or selection against interspecific pollen transfer ([Primack 1985](#ref-primack_1985); [Rathcke & Lacey 1985](#ref-rathcke_1985); [Kessler *et al.* 2020](#ref-kessler_2020)). Therefore, accurately assigning phenological types in the context of pollinator foraging modes will be key to examining the evolution of this trait in the centropogonids, and assessing the role of phenology in pollinator shifts.

*C. granulosus* exhibits a linear flowering rate befitting the ‘steady state’ phenological type described by Gentry ([1974](#ref-gentry_1974)) as “[the production of] a few flowers a day over an extended period of time (usually a month or more)”. It is one of several phenological modes representing an axis of niche partitioning that is thought to contribute to tropical plant diversity ([Gentry 1974](#ref-gentry_1974); [Kessler](#ref-kessler_2020) *[et al.](#ref-kessler_2020)* [2020](#ref-kessler_2020)). Indeed, most hummingbird species exhibit foraging behaviour that is adapted either to steady state or ‘cornucopia’ flowering (sensu [Gentry 1974](#ref-gentry_1974)), with few species able or willing to visit plants of both types ([Kessler](#ref-kessler_2020) *[et al.](#ref-kessler_2020)* [2020](#ref-kessler_2020)). However, beyond qualitative descriptors, there is a need for a quantitative framework to better define and classify phenological types. Because the steady state strategy implies a linear flowering rate, anecdotal observations of phenological type can be tested using the linearity metric implemented here.

   Despite the continental breadth of the *C. granulosus* complex, there is a striking similarity in seasonal flowering duration across its range. Stiles ([1985](#ref-stiles_1985)) recorded a 9-month (~270 days) flowering season of *C. granlosus* in Costa Rica. Considering the peduncle with 68 pedicel scars (see: Results), and the mean flowering rate of 3.94 ± 0.03 days (controls), we estimate that this inflorescence produced flowers for 268 ± 2.04 days. Not only is this a remarkably long flowering season for one individual inflorescence, but this phenological type might occur across the range of *C. granulosus* pollinated by either species of *Eutoxeres*.

   Sicklebills were not marked and our ability to comment on individual behaviour is limited. Nonetheless, the visitation rates support the notion that Buff-tailed Sicklebill is a trapliner. More specifically, this species appears to exhibit ‘traveling exploitation’ (sensu [Sargent *et al.* 2021](#ref-sargent_2021)). We make this designation based on the observations that (1) these hummingbirds have not been recorded defending static territories, and (2) individual food plants are visited 1-2 times per day for brief periods (seconds) of foraging. This is perhaps the fitness advantage promoting the evolution of specializedpollination in *C. granulosus*: Sicklebill visits are infrequent but highly effective in transferring intraspecific pollen, as suggested by the pollinator exclusion experiment. While the behaviours exhibited by *E. condamini* are in accordance with the those documented for White-tipped Sicklebill in Costa Rica ([Stiles 1985](#ref-stiles_1985)), the fine-scale daily movements of *Eutoxeres* (and Hermits generally) have not yet been studied — at present, comparative analyses are constrained by our limited knowledge of these rarely seen pollinators.

Finally, while steady state flowering is not solely indicative of specialization to *Eutoxeres*, we speculate that it is a component of the iterative process by which specialization evolves. That is, steady state flowering may have first co-evolved with traplining hummingbirds ([Rombaut *et al.* 2022](#ref-rombaut_2022)) which excluded visitation by species under stabilizing selection for territoriality. Among the steady state species, floral morphology continued to evolve, further partitioning the steady state species between grades of curvature (Figure 1).

***Concluding Remarks***—

   Pollinator specialization is likely to play an important role in the generation and/or maintenance of species in the mega-diverse Andean Lobelioids. In this study, we confirmed the prediction that *C. granulosus* is pollinated exclusively by Buff-tailed Sicklebill (*E. condamini*) within our study site, where its congener, White-tipped Sicklebill (*E. aquila*), is absent. Furthermore, because Sicklebills exhibit traplining, we find evidence that specialization operates not only through corolla shape, but also the steady state flowering strategy. By documenting plant-pollinator interactions and phenological type, we hope to provide valuable ecological and natural history data needed to test the role of specialization in the rapid diversification of the Andean bellflowers.

#### Data Accessibility

All data and scripts are available as an RStudio Project at: <https://github.com/mannfred/centropogon_eutoxeres>. A Dryad submission will be prepared in coordination with the editorial office.

#### Competing Interests

The authors have no competing interests to declare.

#### Author Contributions

M.B. and Q.C. designed the study, and D.G., J.J., and M.B. conducted the field work. M.B. analysed the data and wrote the first manuscript draft. All authors contributed to writing and editing the final manuscript.

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#### Figure Legends

Figure 1. A: Presumed pollination niches within hummingbird-adapted Centropogon. is total curvature in degrees (see: Boehm et al [2022](#ref-boehm_2022)). Species in reading order: Eugenes fulgens (photo: Ronald E. Thill). Phaethornis guy (photo: Mike Hooper). Eutoxeres condamini (photo: Julian Heavyside). C. valeroi (photo: Laura Lagomarsino). C. solanifolius (photo: Terry Gosliner). C. granulosus (photo: Josh Vandermeulen). Evidence for pollination in each species pair are described in: Colwell ([1973](#ref-colwell_1973)); Snow ([1977](#ref-snow_1977)); this study.

Figure 2. (A): Elevational heatmap of Peru and neighbouring countries. Coloured cells represent meters above sea level. Map generated using tmap v.3.3-2 ([Tennekes 2018](#ref-tennekes_2018)). Study site location is marked with a cross. (B): Montane cloud forests of the eastern Andes (San Pedro, Peru). (C): C. granulosus, an understory vine often flowering at forest edges and treefall gaps.

Figure 3. Visitation of C. granulosus by Buff-tailed Sicklebill (E. condamini).

Figure 4. Developmental trajectories for the flowers of C. granulosus, and effects of pollinator exclusion (green) versus the control treatment (orange). The bars represent the median duration spent in each stage. 95% CIs are estimates of when a stage could end. At stage E, where some individuals begin, others will have already finished and moved onto stage F. No fruits were produced by plants with pollinators excluded.

Figure 5. Flowering rates in C. granulosus. The -axis represents the number of days elapsed since the first flower opened. The -axis counts the cumulative number of flowers opened since =0, not the number of flowers open simultaneously. Each line shows the flowering rate of an individual belonging to the exclusion treatment (green) or control group (orange). Rates vary between individuals (=0.027, =2.70, =1.91), but do not vary between treatments (=0.200, =1.40, =0.99).

#### 

**Appendix for: Floral phenology of an Andean bellflower and pollination by Buff-tailed Sicklebill**

#### Further notes on methods

#### *Visit duration*

To estimate the duration of *E. condamini* visits, we considered that the camera traps took photos in sets of five, lasting less than 3 seconds. To make a conservative estimate, we assume the five photos take 3 seconds. For any 5-photo set in which *E condamini* appears, we assume 3 seconds visitation. For example, during visitation, if *E. condamini* appears in two 5-photo sets, we assume a 2 second (= 6 second) visit, even if the hummingbird appeared in only a subset of the 10 photos.

#### *Landmarking and calculating curvature*

In Figure 1 (main text) we present a graphical illustration of the range of pollination niches within the centropogonids. To compute total curvature (sensu [Boehm *et al.* 2022](#ref-boehm_2022)), we used the following protocol. First, images were imported into *tpsUtil* ([Rohlf 2015](#ref-rohlf_2015)). This .tps file is used by *tpsDig* ([Rohlf 2015](#ref-rohlf_2015)) for landmark assignment. We then placed the following two landmarks on each flower: (A) the base of the dorsal side of the corolla tube where the petals attach to the receptacle and (B) the apex of the dorsal petal. Nine additional sliding semi-landmarks were then placed between the two landmarks, outlining the dorsal arc of the corolla tube. For the hummingbirds, the following two landmarks were placed on each bill: (C) the base of the dorsal side of the upper mandible (exposed), and (D) the apex of the bill. Nine semi-landmarks were placed between these landmarks.

The .tps file generated by *tpsDig* was then imported into R v.4.1.1 via readmulti.tps() from geomorph v.4.0.0 ([Adams & Otárola-Castillo 2013](#ref-adams_2013)). We then fit interpolating splines to each landmark configuration, and computed total curvature using curvr v.0.0.1 ([Boehm 2021](#ref-boehm_2021_b)).

#### *Phenological modeling*

To model flowering phenology of *C. granulosus*, we fit the following linear model to the rate of anthesis and senescence for each inflorescence that produced at least five flowers ( = 5 controls, = 5 pollinator excluded):

   Where is the cumulative number of flowers produced on an inflorescence at =, is the intercept, is the flowering rate, and is the residual error.

   To determine if pollinator exclusion affected the total number of flowers produced, we fit the linear model:

   Where is the intercept, is a coefficient, and is the residual error.

# Appendix Tables

Table A1: Locations in San Pedro monitored for Sicklebill visitation to C. granulosus. The first column lists the C. granulosus individual identifiers.

|  |  |  |  |
| --- | --- | --- | --- |
| name | latitude | longitude | elevation |
| CNTRPGN 1-10 | -13.05684 | -71.54469 | 1306.706 |
| CNTRPGN 11 | -13.05603 | -71.54515 | 1301.995 |
| CNTRPGN 12-15 | -13.05928 | -71.54773 | 1381.661 |
| CNTRPGN 16-20 | -13.05900 | -71.54666 | 1323.870 |
| CNTRPGN 21-23 | -13.05921 | -71.54690 | 1330.937 |
| CNTRPGN 24-32 | -13.05932 | -71.54778 | 1345.147 |
| CNTRPGN 33-41 | -13.05821 | -71.54805 | 1359.792 |
| CNTRPGN 42 | -13.05720 | -71.54699 | 1370.250 |
| CNTRPGN 43-50 | -13.05728 | -71.54672 | 1368.063 |
| CNTRPGN 51-53 | -13.05563 | -71.54676 | 1358.099 |
| CNTRPGN 54-60 | -13.05696 | -71.54784 | 1398.831 |

Table A2: Stages of floral development in C. granulosus.

|  |  |  |
| --- | --- | --- |
| Stage | Description | Median duration days |
| A | Flower primordia appears above bracts. No curvature and red-orange pigmentation is not continuous around the base. Flower up to 9 mm tall (as measured from the top of the bracts). Basal diameter up to 4 mm. | 22.3 |
| B | Initiation of curvature, creating 90 degree angle. Red-orange pigmentation is continuous around the base. Flower up to 10 mm tall. Basal diameter up to 6 mm. | 6.1 |
| C | Growth phase. 180 degree angle formed. Red-orange pigmentation outweighs yellow. Flower 14 to 20 mm tall. Basal diameter 6 - 8 mm. | 6.3 |
| D | Pre-anthesis. >180 degree angle formed. Flower 30 mm tall. Basal diameter 7 - 8 mm. | 8.6 |
| E | Anthesis. Mature male-phase flower. Flower 34 -36 mm tall. Basal diameter 7 - 8 mm. | 2.6 |
| F | Female-phase flower. Pistil grows overtop of the pollen trap. Flower up to 36 mm tall. Basal diameter up to 10 mm. | 2.4 |
| G | Senescing flower. Petals wilting but retained. Basal diameter 8 - 10 mm. | 5.3 |
| H | Berry development. Petals senesced and lost. Basal diameter grows from 11 - 17 mm. | 24.2 |

Table A3: Camera trap records of E. condamini.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Date observed | Time of day | Feeding mode | Visit duration seconds | Temperature celcius | Centropogon ID | Flower ID |
| Aug\_18\_2017 | 12:36 | hovering | 3 | 19 | 1 | 1 |
| Aug\_22\_2017 | 10:38 | hovering | 3 | 21 | 1 | 1 |
| Aug\_22\_2017 | 10:38 | hovering | 3 | 21 | 1 | 2 |
| Aug\_22\_2017 | 15:54 | hovering | 3 | 20 | 1 | 1 |
| Aug\_22\_2017 | 10:39 | hovering | 3 | 20 | 2 | 1 |
| Aug\_23\_2017 | 10:24 | hovering | 3 | 19 | 1 | 2 |
| Aug\_24\_2017 | 7:17 | perching | 3 | 17 | 1 | 1 |
| Aug\_24\_2017 | 7:17 | hovering | 3 | 17 | 1 | 2 |
| Aug\_25\_2017 | 16:27 | inspecting | 3 | 19 | 3 | NA |
| Aug\_26\_2017 | 5:52 | hovering | 3 | 15 | 4 | 1 |
| Sep\_15\_2017 | 5:24 | hovering | 3 | 16 | 5 | 1 |
| Sep\_16\_2017 | 5:56 | inspecting | 3 | 15 | 5 | NA |
| Sep\_19\_2017 | 5:36 | perching | 3 | 14 | 5 | 2 |
| Sep\_19\_2017 | 7:15 | perching | 3 | 16 | 6 | 1 |

Table A4: Camera trap records of S. geofryii.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Date observed | Time of day | Feeding mode | Temperature celcius | Centropogon ID | Flower ID |
| Sep\_11\_2017 | 9:58 | hovering | 20 | 7 | 1 |
| Sep\_11\_2017 | 13:03 | hovering | 22 | 7 | 1 |
| Sep\_11\_2017 | 13:55 | hovering | 23 | 7 | 1 |
| Sep\_11\_2017 | 15:01 | hovering | 23 | 7 | 1 |
| Sep\_11\_2017 | 16:11 | hovering | 22 | 7 | 1 |
| Sep\_14\_2017 | 10:44 | hovering | 21 | 7 | 2 |
| Sep\_14\_2017 | 11:42 | hovering | 22 | 7 | 2 |
| Sep\_14\_2017 | 13:10 | hovering | 21 | 7 | 2 |
| Sep\_14\_2017 | 14:32 | hovering | 21 | 7 | 2 |
| Sep\_14\_2017 | 16:54 | hovering | 21 | 7 | 2 |

# Appendix Figure Legends

Figure A1. Fused anther hairs forming a scale and serving as a lever to deposit pollen (red arrow). This individual has finished the male phase and is in transition to the female phase — the stigma will continue to extend past the scale and unfold when receptive (white arrow).

Figure A2. Trait matching in Buff-tailed Sicklebill and C. granulosus observed at the study site. Photo used with permission from J. Heavyside (UBC).

Figure A3. Wire cages used to exclude avian visitors from accessing the nectaries of C. granulosus. Further details on the design can be found in Sun et al. ([2017](#ref-sun_2017)).

Figure A4. Still frames extracted from a video recording of E. condamini pollinating C. granulosus. A: The hummingbird approaches and inspects an inflorescence without any open flowers. B: A second inflorescence with an open flower is approached. C: To insert its bill, E. condamini hovers below the flower opening and tilts its head backwards. D: During feeding, its head is at eye-level with the corolla opening and the anther/stigma is in contact with the crown.

Figure A5. A long-nosed bat (Glossophaginae) recorded near an inflorescence of C. granulosus with several developing berries.

Figure A6. A rodent (Muridae, bottom left) recorded near an inflorescence of C. granulosus (top left) with several developing berries.

Figure A7. Signs of frugivory of a C. granulosus berry.

Figure A8. Herbivory of a C. granulosus flower by a larval lepidoptran.

Figure A9. A stingless bee (Meliponini) collecting pollen from an anther scale of C. granulosus.

Figure A10. Inflorescence of C. granulosus with a multitude of peduncle scars (red arrow) suggestive of an extended flowering peak.

Figure A11. Buff-tailed Sicklebill visiting Heliconia aemygdiana Burle-Marx, and using the floral bract as a perch during feeding.

Figure A12. Recorded visits to C. granulosus by Buff-tailed Sicklebill. Visit data is compiled from six C. granulosus individuals (see: Table S3). ‘AM’ is defined as 12:00am-11:59am and ‘PM’ is 12:00pm-11:59pm.

# References

Abrahamczyk, S., Poretschkin, C. & Renner, S.S. (2017). Evolutionary flexibility in five hummingbird-plant mutualistic systems: Testing temporal and geographic matching. *Journal of Biogeography*, **44**, 1847–1855.

Adams, D.C. & Otárola-Castillo, E. (2013). Geomorph: An R package for the collection and analysis of geometric morphometric shape data. *Methods in Ecology and Evolution*, **4**, 393–399.

Allison, P.D. (2014). *Event history and survival analysis: Regression for longitudinal event data*. SAGE publications Inc., Thousand Oaks, CA.

Armbruster, W.S. (2014). Floral specialization and angiosperm diversity: Phenotypic divergence, fitness trade-offs and realized pollination accuracy. *AoB Plants*, **6**.

Armbruster, W.S. (2017). The specialization continuum in pollination systems: Diversity of concepts and implications for ecology, evolution and conservation. *Functional Ecology*, **31**, 88–100.

Boehm, M.M.A. (2018). Biting the hand that feeds you: Wedge-billed hummingbird is a nectar robber of a sicklebill-adapted Andean bellflower. *Acta Amazonica*, **48**, 146–150.

Boehm, M.M.A. (2021). curvr: an R package for measuring total curvature from landmarked specimens. *R package version 0.0.1*, **https://github.com/mannfred/curvr**.

Boehm, M.M.A., Jankowski, J.E. & Cronk, Q.C.B. (2022). Plant-pollinator specialization: Origin and measurement of curvature. *The American Naturalist*, **199**, 206–222.

Boehm, M.M.A., Scholer, M.N., Kennedy, J.J.C., Heavyside, J.M., Daza, A., Guevara-Apaza, D. & Jankowski, J.E. (2018). The Manú Gradient as a study system for bird pollination. *Biodiversity Data Journal*, **6**.

Colwell, R.K. (1973). Competition and coexistence in a simple tropical community. *The American Naturalist*, **107**, 737–760.

Colwell, R.K., Betts, B.J., Bunnell, P., Carpenter, F.L. & Feinsinger, P. (1974). Competition for the nectar of *Centropogon valerii* by the hummingbird *Colibri thalassinus* and the flower-piercer *Diglossa plumbea*, and its evolutionary implications. *The Condor*, **76**, 447–452.

Feinsinger, P. & Colwell, R.K. (1978). Community organization among neotropical nectar-feeding birds. *American Zoologist*, **18**, 779–795.

Gentry, A.H. (1974). Flowering phenology and diversity in tropical Bignoniaceae. *Biotropica*, **6**, 64–68.

Gill, F.B. (1987). Ecological fitting: Use of floral nectar in *Heliconia stilesii* Daniels by three species of hermit hummingbirds. *The condor*, **89**, 779–787.

Hinkelmann, C. & Boesman, P.F.D. (2020). Buff-tailed Sicklebill (*Eutoxeres condamini*), version 1.0. Birds of The World (eds J. del Hoyo, A. Elliott, J. Sargatal, D.A. Christie & E. de Juana). Cornell Lab of Ornithology, Ithaca, NY.

Jackson, C. (2016). flexsurv: A platform for parametric survival modeling in R. *Journal of Statistical Software*, **70**, 1–33.

Kay, K.M. & Sargent, R.D. (2009). The role of animal pollination in plant speciation: Integrating ecology, geography, and genetics. *Annual Review of Ecology, Evolution, and Systematics*, **40**, 637–656.

Kessler, M., Abrahamczyk, S. & Krömer, T. (2020). The role of hummingbirds in the evolution and diversification of Bromeliaceae: Unsupported claims and untested hypotheses. *Botanical Journal of the Linnean Society*, **192**, 592–608.

Kroll, M.H., Præstgaard, J., Michaliszyn, E. & Styer, P.E. (2000). Evaluation of the extent of nonlinearity in reportable range studies. *Archives of Pathology & Laboratory Medicine*, **124**, 1331–1338.

Ku, H.H. (1966). Notes on the use of propagation of error formulas. *Journal of Research of the National Bureau of Standards*, **70**, 263–273.

Lagomarsino, L.P., Condamine, F.L., Antonelli, A., Mulch, A. & Davis, C.C. (2016). The abiotic and biotic drivers of rapid diversification in Andean bellflowers (Campanulaceae). *New Phytologist*, **210**, 1430–1442.

Lagomarsino, L.P., Forrestel, E.J., Muchhala, N. & Davis, C.C. (2017). Repeated evolution of vertebrate pollination syndromes in a recently diverged Andean plant clade. *Evolution*, **71**, 1970–1985.

Lagomarsino, L.P. & Muchhala, N. (2019). A gradient of pollination specialization in three species of Bolivian *Centropogon*. *American Journal of Botany*, **106**, 633–642.

Maglianesi, M.A., Blüthgen, N., Böhning-Gaese, K. & Schleuning, M. (2015). Functional structure and specialization in three tropical plant–hummingbird interaction networks across an elevational gradient in Costa Rica. *Ecography*, **38**, 1119–1128.

Maglianesi, M.A., Blüthgen, N., Böhning-Gaese, K. & Schleuning, M. (2014). Morphological traits determine specialization and resource use in plant–hummingbird networks in the Neotropics. *Ecology*, **95**, 3325–3334.

Morrison, B.M. & Mendenhall, C.D. (2020). Hummingbird–plant interactions are more specialized in forest compared to coffee plantations. *Diversity*, **12**, 126.

Naskrecki, P. & Colwell, R.K. (1998). *Systematics and host plant affiliations of hummingbird flower mites of the genera Tropicoseius Baker & Yunker and Rhinoseius Baker & yunker (Acari: Mesostigmata: Ascidae)*. Entomological Society of America, Lanham, MD.

Nentwig, W. & Christenson, T.E. (1986). Natural history of the non-solitary sheetweaving spider *Anelosimus jucundus* (Araneae: Theridiidae). *Zoological Journal of the Linnean Society*, **87**, 27–35.

Primack, R.B. (1985). Patterns of flowering phenology in communities, populations, individuals, and single flowers. *The population structure of vegetation*, pp. 571–593. Springer.

R Core Team. (2017). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria.

Rathcke, B. & Lacey, E.P. (1985). Phenological patterns of terrestrial plants. *Annual Review of Ecology and Systematics*, **16**, 179–214.

Ricklefs, R.E. & Scheuerlein, A. (2002). Biological implications of the weibull and gompertz models of aging. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, **57**, B69–B76.

Rico-Guevara, A., Hurme, K.J., Elting, R. & Russell, A.L. (2021). Bene“fit” assessment in pollination coevolution: Mechanistic perspectives on hummingbird bill-flower matching. *Integrative and Comparative Biology*, **https://doi.org/10.1093/iob/oby006**.

Robinson, D., Hayes, A. & Couch, S. (2021). broom: Convert statistical objects into tidy tibbles. *R package version 0.7.6*, [**https://CRAN.R-project.org/package=broom**](https://CRAN.R-project.org/package=broom).

Rohlf, F.J. (2015). The tps series of software. *Hystrix*, **26**.

Rombaut, L.M., Capp, E.J., Hughes, E.C., Varley, Z.K., Beckerman, A.P., Cooper, N. & Thomas, G.H. (2022). The evolution of the traplining pollinator role in hummingbirds: Specialization is not an evolutionary dead end. *Proceedings of the Royal Society B*, **289**, 20212484.

Salinas, N., Malhi, Y., Meir, P., Silman, M., Roman Cuesta, R., Huaman, J., Salinas, D., Huaman, V., Gibaja, A., Mamani, M. & others. (2011). The sensitivity of tropical leaf litter decomposition to temperature: Results from a large-scale leaf translocation experiment along an elevation gradient in Peruvian forests. *New Phytologist*, **189**, 967–977.

Sargent, A., Groom, D. & Rico-Guevara, A. (2021). Locomotion and energetics of divergent foraging strategies in hummingbirds: A review. *Integrative and Comparative Biology*, **https://doi.org/10.1093/icb/icab124**.

Shrivastav, V. (2019). Lin.eval: Perform polynomial evaluation of linearity. *R package version 0.1.2*, **https://CRAN.R-project.org/package=lin.eval**.

Snow, B.K. (1977). Feeding behavior of two hummingbirds in a Costa Rican montane forest. *The Wilson Bulletin*, **89**, 613–616.

Sonne, J., Zanata, T.B., Martı́n González, A.M., Cumbicus Torres, N.L., Fjeldså, J., Colwell, R.K., Tinoco, B.A., Rahbek, C. & Dalsgaard, B. (2019). The distributions of morphologically specialized hummingbirds coincide with floral trait matching across an Andean elevational gradient. *Biotropica*, **51**, 205–218.

Stein, B.A. (1992). Sicklebill hummingbirds, ants, and flowers. *BioScience*, **42**, 27–34.

Stein, B.A. (1987). Systematics and evolution of *Centropogon* subg. *Centropogon* (Campanulaceae: Lobelioideae). *Ph.D. dissertation. Washington University, St. Louis, WA*.

Stiles, F.G. (1985). Seasonal patterns and coevolution in the hummingbird-flower community of a Costa Rican subtropical forest. *Ornithological Monographs*, **36**, 757–787.

Suarez, R.K. & Gass, C.L. (2002). Hummingbird foraging and the relation between bioenergetics and behaviour. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, **133**, 335–343.

Sun, S.-G., Huang, Z.-H., Chen, Z.-B. & Huang, S.-Q. (2017). Nectar properties and the role of sunbirds as pollinators of the golden-flowered tea *Camellia petelotii*. *American Journal of Botany*, **104**, 468–476.

Temeles, E.J., Liang, J., Levy, M.C. & Fan, Y.-L. (2019). Floral isolation and pollination in two hummingbird-pollinated plants: The roles of exploitation barriers and pollinator competition. *Evolutionary Ecology*, **33**, 481–497.

Temeles, E.J., Linhart, Y.B., Masonjones, M. & Masonjones, H.D. (2002). The role of flower width in hummingbird bill length-flower length relationships. *Biotropica*, **34**, 68–80.

Tennekes, M. (2018). tmap: Thematic maps in R. *Journal of Statistical Software*, **84**, 1–39.

Weiss, M.R. (1996). Pollen-feeding fly alters floral phenotypic gender in *Centropogon solanifolius* (Campanulaceae). *Biotropica*, **28**, 770–773.

Westerkamp, C. (1990). Bird-flowers: Hovering versus perching exploitation. *Botanica Acta*, **103**, 366–371.