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

**Author Names**: [removed for double blind review]

**Corresponding Author**: [removed for double blind review]

**Author affiliations**: [removed for double blind review]

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#### Data and Code Availability

All data and scripts used in this study will be deposited in the Dryad Digital Repository in coordination with the Editorial Office.

#### 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 ([Lagomarsino and Muchhala 2019](#ref-lagomarsino_2019)). Whether specialized mutualisms are 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 and Sargent 2009](#ref-kay_2009); [Armbruster 2014](#ref-armbruster_2014)).

   One diverse clade of *Centropogon*, the ‘eucentropogonids’ (38 spp.), evolved after what is apparently 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*). We test the hypothesis that *C. granulosus* is solely pollinated by Sicklebills, and has functional characters (floral morphology and flowering phenology) that facilitate this.

*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 *Centropogon* ([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. 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 and 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*. 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. 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 S1).

***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 S3). Wire cages prevent hummingbirds from accessing the flowers while allowing invertebrates to move freely. An additional ten inflorescences 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 S2, Figure 3). 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 and 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 as a visitor to *Centropogon granulosus* flowers (Figs. 2 and S4). 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 S12, Table S3). 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 S4). Further details of *S. geoffroyi* behaviour can be found in Boehm ([2018](#ref-boehm_2018b)). No other hummingbirds were recorded visiting these flowers.

Figure 1. A: Presumed pollination niches within hummingbird-adapted Centropogon. K_{tot} is total curvature in degrees see: Boehm et al(see: Boehm et al 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); Snow (1977); this study. B: Visitation of C. granulosus by Buff-tailed Sicklebill.

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   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 S4). 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 S7).

   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 and 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 and Christenson 1986](#ref-nentwig_1986)). We also recorded a larval lepidopteran inhabiting a flower (Figure S8), and a stingless bee (Meliponini) collecting pollen from the anther scale (Figure S9).

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

   We identified and described eight stages of floral development in *C. granulosus* (Table S2, Figure 2). 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 S2).

   These eight stages were used to compare developmental differences between control and pollinator-excluded flowers (Figure 2). 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 abcission scars on the peduncle of an individual not included in this study (Figure S10).

   Linear models accurately described flowering rate (Figure 3): 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 3). 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.

Figure 2. 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.

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Figure 3. Flowering rates in C. granulosus. The x-axis represents the number of days elapsed since the first flower opened. The y-axis counts the cumulative number of flowers opened since t=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 (p=0.027, t_8=2.70, d=1.91), but do not vary between treatments (p=0.200, t_8=1.40, d=0.99).

Figure 3. 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).

#### Discussion

***Buff-tailed Sicklebill is a 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 (Colwell et al., submitted), hovering is one of the most energetically expensive modes of locomotion ([Suarez and 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 (Colwell et al., submitted). 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 1). 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 S11). 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 and 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 and 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 et al. 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 et al. 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. Broadly, the behaviours exhibited by *E. condamini* are in accordance with the foraging behaviours documented for White-tipped Sicklebill in Costa Rica ([Stiles 1985](#ref-stiles_1985)). However, 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.

***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 within our study site, where its congener, White-tipped Sicklebill, 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 AVAILABILITY

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.

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