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Research Article

Reproductive phenology and floristic composition of a peri-urban forest fragment in the Colombian Andes

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Abstract

Peri-urban forests play a key role in mitigating climate change and conserving biodiversity within expanding urban landscapes. However, the ecological processes that sustain their functionality—such as the reproductive phenology of plant species—have been poorly documented in the Colombian Andes. This study aimed to conduct a floristic inventory and qualitatively evaluate the phenological events of a peri-urban forest in the Municipality of Popayán (Cauca, Colombia). Sampling was carried out through direct observation of fertile individuals and recording of reproductive phases (flowering and fruiting). A total of 68 species belonging to 31 angiosperm families were identified, with Orchidaceae, Rubiaceae and Araceae being the most diverse. The predominant growth forms were herbs and shrubs, suggesting that the forest is at an intermediate stage of ecological succession. Phenological events showed marked temporal variation: flowering peaks occurred mainly in March, April and September during the monitoring period. These temporal patterns indicate an association between reproductive phenophases and climatic variation. *Vismia baccifera*, *Besleria solanoides* and *Psychotria carthagenensis* stood out for maintaining prolonged flowering and fruiting, providing continuous resources to pollinators and dispersers, thereby reinforcing their ecological role in the regeneration and stability of the ecosystem. The results highlight the importance of peri-urban forest fragments as biodiversity refuges and providers of essential ecosystem services, even under anthropogenic pressures. Additionally, they underscore the need to conserve these fragments, which function as biological corridors and key spaces for ecological connectivity and the resilience of Andean ecosystems.

Key words: Ecology, floristic composition, peri-urban forest, reproductive phenology.

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Introduction

Forests play a fundamental role in mitigating climate change by contributing to hydrological and climatic regulation, carbon sequestration and air purification in urban and industrial areas (Gakidou et al. 2017; Riondato et al. 2020). In particular, peri-urban forests—located at the interface between rural and urban environments—perform essential ecological functions such as serving as biological corridors, refuges for biodiversity and spaces that promote the

well-being of local communities (Livesley et al. 2016). However, rapid urban growth, the expansion of forest monocultures and pressure from agricultural activities have substantially modified Andean landscapes, causing fragmentation and the progressive loss of native forest remnants (Hansen et al. 2020).

Floristic inventories constitute a key tool for establishing baseline information on plant diversity and guiding conservation strategies, while phenological studies allow us to understand how plants respond to seasonal climatic variation—an essential aspect for interpreting the ecological dynamics of ecosystems (Herrera and Pellmyr 2002). Through the analysis of events such as flowering and fruiting, it is possible to identify ecological and reproductive patterns that reflect interactions between species and their environment (Corredor-Londoño et al. 2020). In tropical ecosystems, these patterns determine the temporal availability of resources such as nectar, pollen and fruits, which sustain plant–animal interactions and the overall functioning of biological communities (de Medeiros et al. 2020).

Nevertheless, anthropogenic pressure derived from urbanisation alters these cycles, reducing the ecological functionality of remnant forests and their capacity to sustain mutualistic networks. Consequently, understanding reproductive phenology in peri-urban contexts is important for exploring ecological responses and potential successional patterns in ecosystems, particularly in regions such as the Colombian Andes, where knowledge remains limited. Despite recent advances in the study of functional traits associated with urban–rural coverage (Salamanca-Fonseca et al. 2024) and sustainable land-use planning in metropolitan green infrastructure (La Rota-Aguilera et al. 2024), studies linking floristic composition with reproductive phenological patterns in peri-urban mountain landscapes remain scarce. Additional evidence suggests that the regeneration of secondary Andean forests can restore part of their ecological functionality and contribute to connectivity between fragments (Ramos et al. 2025).

Therefore, studying peri-urban forest fragments in the Colombian Andes is important for understanding how the reproductive processes of native flora are expressed under conditions of fragmentation and urban influence. In this context, the following research question was posed: what reproductive phenological events and floristic composition characterise angiosperms in a peri-urban forest fragment in the Colombian Andes?

Consequently, the objective of this study was to conduct an inventory of angiosperms and to qualitatively record flowering and fruiting events during the study period to describe the floristic composition of the forest fragment and to explore possible temporal patterns in reproductive phenology under the climatic conditions observed during the monitoring period, as well as to discuss their importance for conservation.

Materials and methods

Study area

This study was conducted in a peri-urban forest located in the Village of La Claridad, in the Municipality of Popayán, Cauca, Colombia. The forest is surrounded by pastures and agricultural areas and forms a transition zone between the urban area of Popayán and the surrounding rural landscape. The

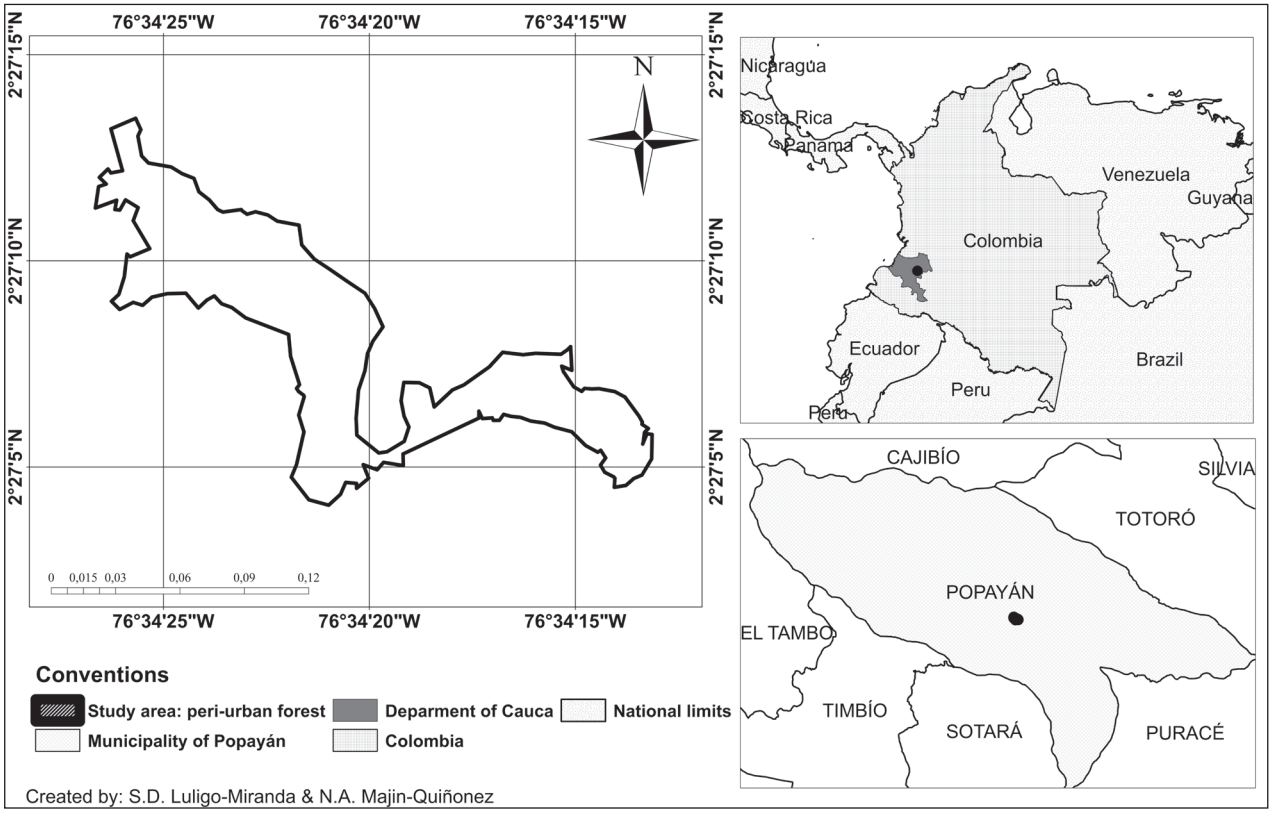


Figure 1. Study area in the Village of La Claridad, Municipality of Popayán, Department of Cauca, Colombia.

altitude of the site ranges from 1830 to 1900 m a.s.l., with the central coordinates of 2.452254, -76.572497 (latitude and longitude). The total extent of the peri-urban forest is 2.96 hectares (Fig. 1).

The climate characterisation of the study area was based on daily precipitation and air temperature records for the year 2025, obtained from a local monitoring station located 1.19 km from the study site, as part of the IDEAM-ENANDES Colombia Community Monitoring project (Improving the Adaptive Capacity of Andean Communities through Climate Services). These meteorological data were used to describe the climatic conditions during the sampling period and to provide a climatic context for interpreting the recorded phenological patterns. The average annual temperature for 2025 was 18.4 °C and the total annual precipitation was 1831.1 mm.

Species inventory

For the species inventory, an exploratory field survey approach was conducted across the entire fragment (2.96 ha), following the general recommendations of Mostacedo and Fredericksen (2000) and Villareal et al. (2006). The area was surveyed through two monthly field walks covering all zones of the fragment, without establishing fixed plots or quadrats, to maximise spatial coverage and record the highest possible number of reproductive events between January and September 2025. During each sampling period, the fragment was systematically surveyed.

The survey focused primarily on individuals presenting observable fertile structures, since reproductive organs are essential for reliable taxonomic

identification in many angiosperm groups (Gaem et al. 2022) and also to allow the recording of the reproductive phenophases evaluated in this study. However, to document the angiosperm species present in the fragment, sterile individuals were also recorded when identification was possible, based on vegetative characters or when they corresponded to well-known species in the study area. In some taxonomically complex groups, identification at the species level was not always possible, even with fertile material, despite the support from specialists and the use of taxonomic literature and reference collections. As the inventory focused on phenological events, not all non-fertile individuals could be included. Consequently, the recorded species richness may be underestimated and the inventory results are, therefore, presented as a qualitative characterisation of the floristic composition of the study area.

Additionally, diversity indices such as these were not calculated because the sampling design was based on exploratory field walks without standardised plots, fixed sampling units or quantitative abundance estimates. Therefore, the data obtained were considered more appropriate for qualitative floristic characterisation than for quantitative diversity analyses.

During each sampling event, the following information was recorded: locality, geographic coordinates, elevation, collection date, collection number and the family, genus, growth form and morpho-descriptive characteristics of each specimen, including corolla colour, presence of exudates, odour, leaf arrangement, colouration of the adaxial and abaxial leaf surfaces and stem characteristics, which were used for comparison with reference specimens during taxonomic identification. For each species, between two and four fertile specimens were collected for herbarium deposition. Specimens were pressed in newspapers and processed at the CAUP Herbarium of the University of Cauca for identification through comparison with reference collections and the use of taxonomic databases such as Plants of the World Online (POWO) and Tropicos. Additionally, photographic documentation of the sampled individuals was carried out, focusing on the most relevant flowering and fruiting structures to support accurate taxonomic determination.

Recording of phenological data

Phenological records were obtained from January to September 2025 from individuals presenting reproductive structures (flower/fruit), corresponding to the 68 identified species. The monitoring of phenological events was carried out on all previously recorded fertile individuals of each species showing reproductive phenophases; observations were based on all fertile individuals encountered during field walks within the study fragment; the number of individuals per species varied depending on its occurrence in the area. Whenever possible, the same individuals encountered during field walks were observed during successive sampling visits. All observed individuals were georeferenced and visually recognised throughout the monitoring period to ensure accurate identification and follow-up during the study.

Each individual was considered an observation unit, while the sampling unit used for the analysis corresponded to species per month. Due to the sampling design, based on field walks without fixed plots or standardised counts, the number of individuals per species was not constant and did not allow for a

reliable estimation of abundance. Therefore, abundance models were not applied and the analysis was based on the presence and absence of phenophases per species in each month.

Three main phenophases were observed: (1) open flowers; (2) fruiting with mature fruits and (3) fruiting with green fruits (Urrego et al. 2016). The study focused on reproductive phenophases only, since the objective was to characterise reproductive phenology in relation to floristic composition and the sampling design was orientated towards recording reproductive events. The temporal occurrence of each phenophase was estimated from the number of months in which it was recorded per species across all observations during the nine months, corresponding to approximately 75% of the annual cycle; therefore, the results represent a partial characterisation of the phenological cycle.

Throughout this period, plant species presenting a reproductive state were recorded along with their taxonomic and location data. The information obtained from phenological observations was systematised and organised into a binary presence/absence matrix (where 0 indicates absence and 1 indicates presence) to optimise storage and subsequent analysis, which was performed in RStudio version 2025.09.1+401 using the ggplot package. Given the qualitative nature of the analysis, data analyses focused on the frequency of phenophase occurrence per species and month, without applying abundance models. This methodological approach follows recent recommendations in phenology for fragmented landscapes (Mohanta et al. 2024) and for peri-urban forests (Yin et al. 2024).

Statistical analysis

Phenological data were analysed using both descriptive statistics and circular statistics approaches in order to evaluate the temporal distribution of reproductive phenophases.

Temporal concentration of reproductive phenophases was estimated as the number of species exhibiting flowering and fruiting events per temporal unit (month). This approach allowed the identification of periods with higher reproductive activity, based on presence/absence data and was interpreted as a community-level pattern of phenophase occurrence, in a manner analogous to the activity index proposed by Morellato et al. (1990).

To assess seasonality, the seasonality index (r) was calculated, which quantifies the degree of concentration of phenological events throughout the annual cycle. Additionally, the Rayleigh test was applied to determine whether the temporal distribution of events significantly deviates from a uniform distribution, indicating the presence of well-defined seasonal patterns (Fisher 1993).

Furthermore, the non-parametric Kruskal–Wallis test was used to evaluate significant differences in the monthly occurrence of phenophases. No correlation or regression analyses were performed to test statistical relationships between climatic variables and phenological events; therefore, climate data were interpreted descriptively. All analyses were conducted in the R environment (version 2026.01.1+403) (R Core Team 2023), using the tidyverse package for data manipulation (Wickham et al. 2019), ggplot2 for graphical representation (Wickham 2016) and circular for seasonality analyses and circular statistical tests.

Results

The sampling and observations conducted allowed the identification of 68 fertile species belonging to 31 angiosperm families. Of these, 28 species (41.17%) were identified to the species level, 38 (55.88%) to the genus level and two morphospecies (2.94%) were determined only to the family level.

Identifications were carried out using specialised literature and in consultation with taxonomic experts. In some taxonomically complex groups, as species-level determination was not possible, individuals were treated at the genus level following standard practices in floristic studies (Villareal et al. 2006). Although only 41.17% of the taxa were identified at the species level, this limitation is not expected to significantly affect the interpretation of ecological patterns, since analyses of floristic composition and diversity at the genus or family level are accepted in tropical vegetation studies (Luebert et al. 2022). The distribution of genera and species amongst families allows for the recognition of the most diverse taxonomic groups in the study area (Table 1).

The most diverse family in the study area was Orchidaceae, with 11 species (16.18%), followed by Rubiaceae with eight species (11.76%) and Araceae with six species (8.82%). Together, these three families accounted for 36.76% of the recorded floristic richness. The genera with the highest number of species were *Palicourea* and *Anthurium*, each represented by five species.

The dominant growth form in the study area corresponded to herbs, with 21 species (30.88%), followed by shrubs with 20 species (29.41%) and epiphytes with 17 species (25%). The relatively high proportion of epiphytic species indicates the structural complexity and humidity conditions of the

Table 1. Angiosperm families with the number of genera and species present in the study area of Vereda La Claridad, Popayán, Colombia.

Family	Genus	Species	Family	Genus	Species
Actinidiaceae	1	1	Lauraceae	1	1
Araceae	2	6	Lythraceae	1	1
Asteraceae	3	4	Malvaceae	1	1
Campanulaceae	1	1	Melastomataceae	2	3
Chloranthaceae	1	1	Moraceae	1	1
Clusiaceae	1	1	Orchidaceae	7	11
Commelinaceae	1	1	Passifloraceae	1	1
Ericaceae	3	3	Phyllanthaceae	1	1
Euphorbiaceae	2	2	Phytolaccaceae	1	1
Fabaceae	2	2	Piperaceae	1	2
Fagaceae	1	1	Polygalaceae	1	1
Gesneriaceae	2	2	Rubiaceae	4	8
Heliconiaceae	1	1	Siparunaceae	1	1
Hypericaceae	1	1	Solanaceae	2	3
Lamiaceae	2	3	Viburnaceae	1	1
			Zingiberaceae	1	1

Note: This table presents the angiosperm families recorded in the study area of Vereda La Claridad, including the number of genera and species within each family. This Table provides an overview of the taxonomic diversity of flowering plants present in the surveyed zone.

peri-urban forest fragment, which favour the establishment of this growth form. In functional terms, epiphytes can represent an important component of biomass and nutrient recycling, playing a relevant ecological role within the trophic structure of the ecosystem (Henao-Diaz et al. 2012). The observed composition, characterised by a high proportion of herbs and shrubs and a lower representation of trees, may suggest that the forest fragment is undergoing regeneration processes or corresponds to an intermediate stage of succession; however, this interpretation is based exclusively on floristic composition and growth forms rather than on direct structural vegetation measurements.

Considering the 28 species identified at the species level, all were determined to be native to Colombia. This information was verified using the Plants of the World Online (POWO) database and the Catálogo de Plantas de Colombia of the Instituto Humboldt.

Likewise, the threat category of the recorded species was evaluated. In total, 15 species are included in some risk category either at the national level, according to Resolution No. 0126 of the Ministry of Environment and Sustainable Development (6 February 2024) or at the global level, according to the Red List of the International Union for Conservation of Nature (IUCN). The growth habits of these species (herb, bush, epiphyte, tree, little tree and creeper) were also recorded, as this information contributes to understanding their ecological role within the fragment, particularly in relation to fragment structure, regeneration processes and conservation value in peri-urban environments.

Quercus humboldtii Bonpl. It was included in both lists, being classified as Vulnerable (VU) at the national level in Colombia, whereas it is categorised as Least Concern (LC) at the global level according to the IUCN Red List (Table 3).

Phenological measurements were obtained from 19 observations conducted over nine months across the recorded species, resulting in a total of 197 recorded occurrences. Flowering and fruiting phases were present in most observations across the different field campaigns. However, statistical analysis revealed distinct dynamics for each phenophase.

Climatic conditions during the study period exhibited a bimodal precipitation pattern, with relatively higher precipitation values observed in March and May, followed by a gradual decrease towards mid-year, while temperature remained relatively constant (Fig. 2).

Regarding phenological synchrony, the highest concentrations of flowering events were observed during months characterised by relatively higher precipitation, particularly in March and April. In contrast, fruiting showed a more homogeneous temporal distribution, with a greater concentration of events observed in September, during relatively drier conditions (Figs 3, 4). These temporal patterns may suggest a possible association between climatic variation and reproductive phenophases; however, no formal statistical analysis was conducted to evaluate this relationship.

Flowering was the most representative phenophase compared to fruiting. A significant seasonal pattern was detected in flowering (Rayleigh test: $Z = 0.3472$, $p < 0.001$), indicating a non-uniform distribution of these events.

The seasonality index ($r = 0.347$) confirmed a moderate temporal concentration, with marked synchrony in March ($n = 34$), followed by April ($n = 25$) and September ($n = 20$) (Table 4 and Fig. 2).

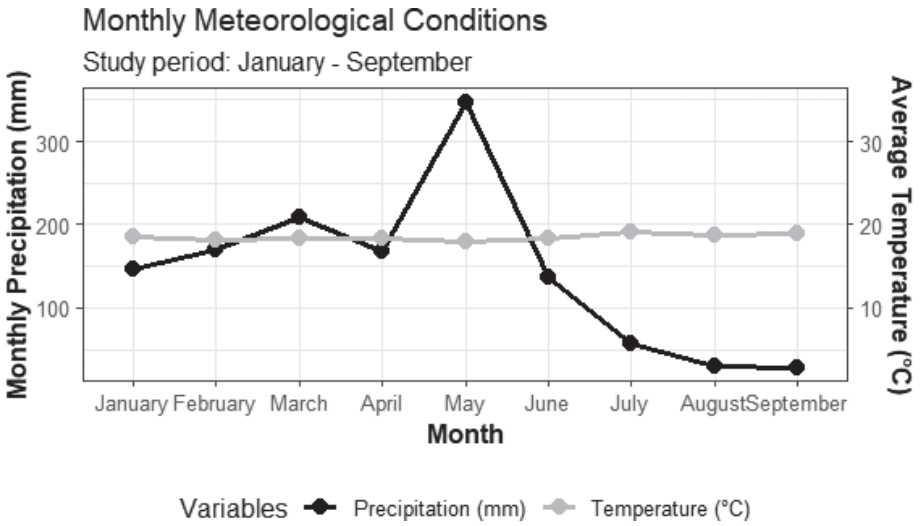


Figure 2. Monthly meteorological conditions (temperature and precipitation).

This monthly variation was supported by the Kruskal–Wallis test, which revealed significant differences in flowering amongst months (χ^2 = 44.993, df = 8, p < 0.001).

At the species level, while species such as *Besleria solanoides*, *Palicourea* sp. 1, *Vismia baccifera* and *Siparuna aspera* exhibited extended flowering periods, others such as *Heliconia burleana*, *Ficus* sp., *Stelis* sp. and *Commelina obliqua* showed flowering restricted to short periods. In contrast, species such as *Xanthosoma* sp., *Comparettia* sp. and *Pavonia schiedeana* did not record any flowering events during the evaluated months (Table 5).

It is important to note that sampling intensity was lower in May due to adverse climatic conditions, which coincided with a reduced detection of flowering events (13.2%). In contrast, fruiting exhibited a more restricted pattern in terms of the number of species, but was more evenly distributed over time (Figs 3, 4). Unlike flowering, fruiting did not show a significant circular seasonality (Rayleigh test: Z = 0.2354, p = 0.0775), suggesting a relatively more homogeneous temporal distribution of fruiting events throughout the study period.

This is reflected in a lower seasonality index (r = 0.235), suggesting that fruit production was temporally less concentrated during the monitoring period (Table 6).

However, fluctuations in the monthly number of fruiting species were detected (Kruskal–Wallis test: χ^2 = 29.643, df = 8, p < 0.001), with a relative peak in September (n = 15, 22.1% of the species), partially coinciding with a decline in flowering activity (Fig. 3 and Table 5).

Species such as *Vismia baccifera*, *Psychotria carthagenensis* and *Besleria solanoides* stood out for their recurrent fruiting across multiple periods, whereas *Bejaria mathewsii* and *Solanum acerifolium* exhibited sporadic and isolated events. In contrast, orchid species (*Stelis*, *Oncidium*, *Comparettia*, *Lepanthes*, *Octomeria* and *Rodriguezia*), *Monnina celastroides*, *Anthurium pedatum*, *Commelina obliqua* and *Burmeistera* sp. did not exhibit fruiting during the study period (Table 6).

The monthly phenological percentages are presented in Table 4, where the months in which flowering was most representative relative to the total number of species (n = 68) can be identified.

Overall, flowering exhibited higher monthly proportions compared to fruiting, indicating a greater participation of species in this phenophase throughout the

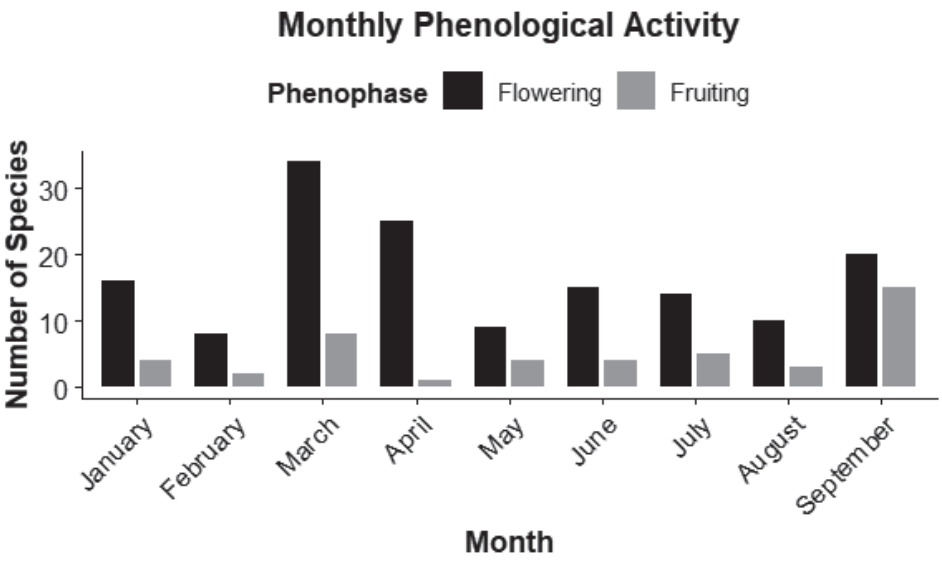


Figure 3. Monthly phenology (flowering/fruiting) by number of species.

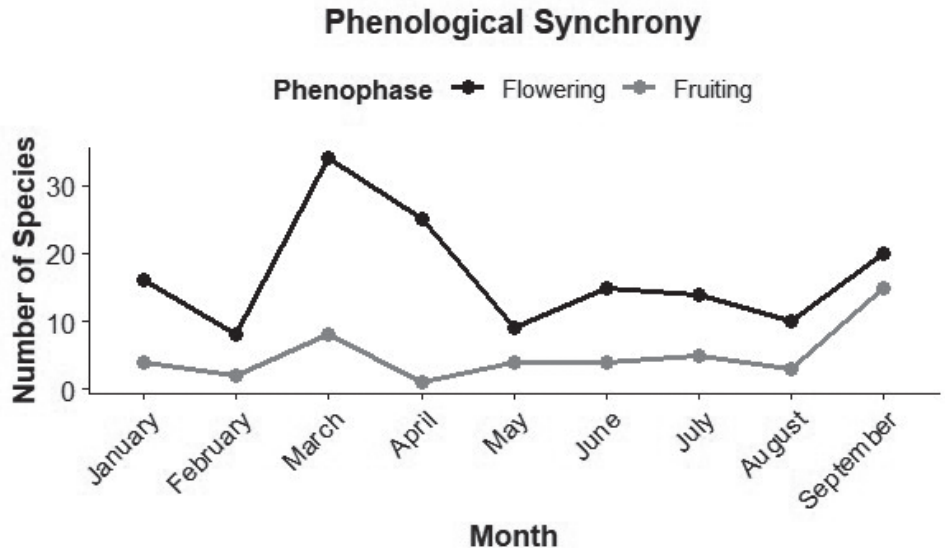


Figure 4. Monthly phenological trend.

study period. In contrast, fruiting consistently showed lower percentages, suggesting a comparatively more restricted distribution in terms of the number of species involved.

Discussion

The floristic inventory conducted in the peri-urban forest of the Village of La Claridad allowed the recording of 68 fertile species belonging to 31 angiosperm families, forming a diverse plant community representative of Andean peri-urban forests. Amongst the families recorded, Orchidaceae, Rubiaceae and Araceae were the most representative in terms of species richness. The high richness of Orchidaceae may indicate that the environmental conditions of the fragment satisfy the ecological requirements of this group, since suitable abiotic and biotic factors favour its growth and reproduction (Davis et al. 1990). Rubiaceae, for its part, is characterised by its wide diversification and

Table 2. Growth forms of the identified plant species.

Habit	Family	Genera	Species	Richness (%) for species
Herb	15	1	21	30.88
Bush	12	14	20	29.41
Epiphyte	4	7	17	25
Tree	5	5	5	7.35
Little tree	3	3	3	4.41
Creeper	1	1	1	1.47
Holoparasite	1	1	1	1.47

Note: This table summarises the growth forms (habits) of the plant species identified in the study area. It reports the number of families, genera and species associated with each habitat type, as well as the percentage contribution of each group to total species richness.

distribution, which has allowed this group to be used to evaluate diversity patterns at different spatial scales (Valois-Cuesta et al. 2016).

In the case of Araceae, its representation may be related to the great variety of life forms that the family presents, including terrestrial, epiphytic and climbing species, which allows it to adapt to different environmental conditions within the forest. This family is also characterised by its variety of life forms (Gámez and Zuluaga 2022). The observed composition, characterised by a high proportion of herbs and shrubs (Table 2) and a lower representation of trees, may suggest that the ecosystem is in a regeneration phase or an intermediate stage of succession. This interpretation is based on growth forms and floristic composition rather than on direct structural measurements such as diameter, density or basal area. This pattern aligns with the classical theory of plant ecological succession, according to which disturbed systems tend to be dominated by fast-growing, short-lived pioneer species that are gradually replaced by longer-lived, slower-growing late-successional species (Poorter et al. 2024).

The peri-urban location of the study area, which is directly adjacent to agricultural zones and pastures, implies that the structure and composition of the forest are influenced by urbanisation and landscape fragmentation. This phenomenon has been extensively documented. Aronson et al. (2014) highlight that urban expansion reduces the diversity of native species and promotes biological homogenisation. Nevertheless, the predominant presence of native plants, including 28 species confirmed as such, indicates that the fragment maintains substantial ecological integrity compared to more degraded urban remnants. In particular, the high representation of Orchidaceae reinforces this interpretation because epiphytic orchids are sensitive bioindicators of habitat quality (Joya et al. 2025), suggesting the persistence of suitable microclimates and a functionally structured forest.

The high presence of epiphytic species may also influence the reproductive phenology patterns observed in the study, given that these plants depend heavily on environmental conditions such as humidity, light availability and the structure of the host tree (Davis et al. 1990). In fragmented peri-urban forests, changes in canopy cover, edge effects and microclimatic variability can modify these conditions, potentially affecting the timing, duration and frequency of flowering and fruiting (Aronson et al. 2014). This phenological variability recorded in the fragment may be partially related to the structural heterogeneity generated by fragmentation processes.

Table 3. Risk category of the species identified in the study area.

Species	Colombia	IUCN	Habit
Saurauia brachybotrys Turcz.	-	LC	Tree
Anthurium carinatum Engl.	-	-	Epiphyte
Anthurium pedatum (Kunth) Endl.	-	-	Herb
Anthurium sanguineum Engl.	-	-	Epiphyte
Clusia alata Planch. & Triana	-	LC	Tree
Commelina obliqua Vahl	-	-	Herb
Bejaria mathewsii Fielding & Gardner	-	LC	Bush
Monotropa coccinea Zucc.	-	-	Holoparisite
Alchornea latifolia Sw.	-	LC	Tree
Quercus humboldtii Bonpl.	VU	LC	Tree
Besleria solanoides Kunth	-	LC	Bush
Heliconia burleana Abalo & G. Morales	-	-	Herb
Vismia baccifera (L.) Triana & Planch.	-	LC	Tree
Aiouea montana (Sw.) R. Rohde	-	LC	Tree
Pavonia schiedeana Steud.	-	-	Herb
Meriania speciosa (Bonpl.) Naudin	-	LC	Little tree
Phytolacca rivinoides Kunth & C. D. Bouché	-	-	Herb
Monnina celastroides (Bonpl.) Chodat	-	-	Herb
Coccocypselum lanceolatum (Ruiz & Pav.) Pers.	-	-	Herb
Posoqueria coriacea M. Martens & Galeotti	-	LC	Little tree
Palicourea allenii (Standl.) Borhidi	-	LC	Bush
Psychotria carthagenensis Jacq.	-	LC	Bush
Siparuna aspera (Ruiz & Pav) A. DC.	-	LC	Little tree
Solanum acerifolium Humb. & Bonpl. ex Dunal	-	-	Herb
Solanum americanum Mill.	-	-	Herb
Miconia theaezans (Bonpl.) Cogn.	-	LC	Bush
Miconia caudata (Bonpl.) DC.	-	LC	Bush
Renealmia caucana Maas	-	-	Herb

Note: This table shows the conservation status of the species identified in the study area, including their risk category according to national (Colombia) and international (IUCN) assessments. This table highlights the presence of species of conservation concern.

Amongst the species of special interest, *Quercus humboldtii* stands out, classified as Vulnerable (VU) at the national level (Resolution 0126 of 2024) and as Least Concern (LC) according to the IUCN. The presence of this species in a peri-urban forest fragment is noteworthy, given that Andean oak forests have experienced a reduction of nearly 60 percent in their cover, primarily due to logging and agricultural expansion (Muñoz and Churio 2014; Avella and Rangel 2017). This finding emphasises the need to implement local conservation and management measures to maintain residual populations and secure genetic connectivity.

Other species of interest were considered, based on their recorded growth habit, as this provides qualitative information about the structure and successional stage of the fragment. The presence of tree species such as *Alchornea latifolia* and *Aiouea montana*, as well as shrub species such as *Miconia theaezans*, *Besleria solanoides* and *Psychotria carthagenensis*, herbaceous species such as Commelina obliqua and *Renealmia caucana*, epiphytes of the

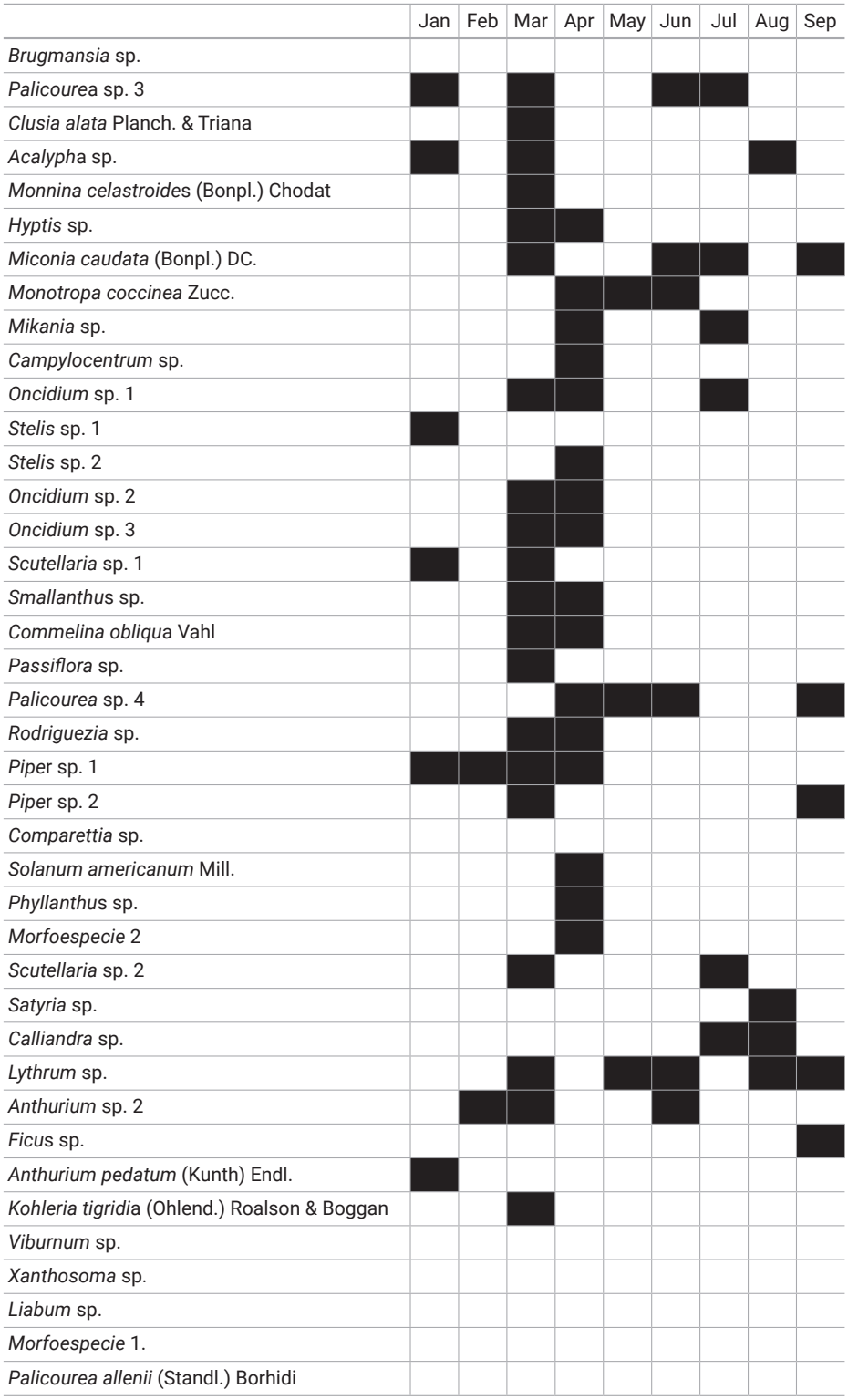
Table 4. Phenological percentages and number of species per month.

Month	Phenological percentage per Month		Number of species per Month	
	Flower	Fruit	Flower	Fruit
January	23.5	5.9	16	4
February	11.8	2.9	8	2
March	50	11.8	34	8
April	36.8	1.5	25	1
May	13.2	5.9	9	4
June	22.1	5.9	15	4
July	20.6	7.4	14	5
August	14.7	4.4	10	3
September	29.4	22.1	20	15
Total, number of species				68

Note: This table summarises the monthly phenological activity of the plant species observed in the study area. It includes the percentage of species flowering and fruiting each month, as well as the total number of species expressing each phenophase. This information reflects seasonal patterns in plant reproduction.

Table 5. Heat map showing the presence/absence of flowering by species and month.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Aiouea montana (Sw.) R. Rohde								■	■
*Palicoure*a sp. 1		■	■	■	■	■	■	■	■
Bejaria mathewsii Fielding & Gardner	■	■	■			■			
*Vismia baccifer*a (L.) Triana & Planch.			■			■	■	■	■
*Siparuna asper*a (Ruiz & Pav) A. DC.		■	■	■	■	■	■	■	■
Burmeistera sp.	■		■						■
Solanum acerifolium Humb. & Bonpl.									■
*Alchornea latifoli*a Sw.	■								
Anthurium sanguineum Engl.			■	■					■
Ingа sp.									
Pavonia schiedeana Steud.									
Anthurium carinatum Engl.									■
Renealmia caucana Maas	■	■	■	■			■		■
Anthurium sp. 1				■					
Palicourea sp. 2			■		■	■	■	■	■
*Posoqueria coriace*a M. Martens & Galeotti						■			
Hedyosmum colombianum Cuatrec.	■		■				■		
*Miconia theaezan*s (Bonpl.) Cogn.		■	■						
Meriania speciosa (Bonpl.) Naudin						■	■	■	
*Quercus humboldti*i Bonpl.									■
*Psychotria carthagenensi*s Jacq.	■		■	■	■				■
Heliconia burleana Abalo & G. Morales	■								■
*Lepanthe*s sp.	■			■					
Octomeria sp.	■								
Saurauia brachybotrys Turcz.			■						
*Coccocypselum lanceolatu*m (Ruiz & Pav.)					■				
*Besleria solanoide*s Kunth	■	■	■	■	■	■	■		■
Phytolacca rivinoides Kunth & C. D. Bouché			■	■		■			■



Note: Heat map showing the flowering phenology of the recorded species from January to September 2025. Black cells indicate the presence of flowering in the corresponding month, while white cells indicate the absence of flowering. Values represent presence/absence records, based on monthly observations for each species.

genus Anthurium and specialised species such as *Monotropa coccinea*, suggests high structural heterogeneity in the study area.

Some studies consider *Miconia theaezans* an indicator of early successional stages (Cantillo et al. 2009); however, due to the lack of abundance data, it is

Table 6. Heat map showing the presence/absence of fruiting by species and month.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Aiouea montana (Sw.) R. Rohde									
Palicourea sp. 1			■					■	■
Bejaria mathewsii Fielding & Gardner	■								
Vismia baccifera (L.) Triana & Planch.			■			■	■	■	■
Siparuna aspera (Ruiz & Pav) A. DC.			■						■
Burmeistera sp.									
Solanum acerifolium Humb. & Bonpl.									■
Alchornea latifolia Sw.	■								
Anthurium sanguineum Engl.									■
Inga sp.									
Pavonia schiedeana Steud.									
Anthurium carinatum Engl.									■
Renealmia caucana Maas	■						■		■
Anthurium sp. 1									
Palicourea sp. 2						■		■	■
Posoqueria coriacea M. Martens & Galeotti						■			
Hedyosmum colombianum Cuatrec.	■		■						
Miconia theaezans (Bonpl.) Cogn.									
Meriania speciosa (Bonpl.) Naudin							■		
Quercus humboldtii Bonpl.									■
Psychotria carthagenensis Jacq.	■	■	■		■				■
Heliconia burleana Abalo & G. Morales	■								■
Lepanthes sp.									
Octomeria sp.									
Saurauia brachybotrys Turcz.			■						
Coccocypselum lanceolatum (Ruiz & Pav.)					■				
Besleria solanoides Kunth			■			■	■		■
Phytolacca rivinoides Kunth & C. D. Bouché									■
Brugmansia sp.									
Palicourea sp. 3			■						
Clusia alata Planch. & Triana									
Acalypha sp.									
Monnina celastroides (Bonpl.) Chodat									
Hyptis sp.					■				■
Miconia caudata (Bonpl.) DC.							■		
Monotropa coccinea Zucc.						■			
Mikania sp.					■				
Campylocentrum sp.				■					
Oncidium sp. 1									
Stelis sp. 1									
Stelis sp. 2									
Oncidium sp. 2									
Oncidium sp. 3									
Scutellaria sp. 1									
Smallanthus sp.									
Commelina obliqua Vahl									

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Passiflora sp.									
Palicourea sp. 4									■
Rodriguezia sp.									
Piper sp. 1									
Piper sp. 2									
Comparettia sp.									
Solanum americanum Mill.				■					
Phyllanthus sp.									
Morfoespecie 2									
Scutellaria sp. 2									
Satyria sp.									
Calliandra sp.									
Lythrum sp.									
Anthurium sp. 2									
Ficus sp.									■
Anthurium pedatum (Kunth) Endl.									
Kohleria tigridia (Ohlend.) Roalson & Boggan									
Viburnum sp.									
Xanthosoma sp.									
Liabum sp.									
Morfoespecie 1.									
Palicourea allenii (Standl.) Borhidi									

Note: Heat map showing the fruiting phenology of the recorded species from January to September 2025. Black cells indicate the presence of fruiting in the corresponding month, while white cells indicate the absence of fruiting. Values correspond to presence/absence records obtained during the monitoring period.

not possible to definitively state that this species indicates an early successional stage in the study area, although its presence could be associated with such conditions. On the other hand, species of the genus Monotropa are entirely microheterotrophic plants that depend on ectomycorrhizal fungal networks associated with forest trees, so their presence is usually restricted to shaded and relatively well-preserved forests. Their occurrence has been documented to be related to ecosystems that maintain suitable conditions for these interactions, potentially associated with more advanced successional stages or a certain degree of forest continuity (Johansson et al. 2017; Holmes 2023).

Overall, the co-existence of pioneer herbs and shrubs with tree species and varied growth forms is characteristic of regenerating ecosystems or those in intermediate successional stages, where colonising species establish themselves after disturbances and are progressively replaced by longer-lived species. However, this interpretation should be considered with caution due to the absence of quantitative abundance data and structural vegetation measurements, as well as the exploratory nature of the sampling design, which did not include standardised plots or fixed sampling units. For this reason, quantitative diversity indices were not estimated and the analysis was focused on qualitative floristic composition and reproductive phenology patterns.

The co-existence of species associated with conserved environments and others adapted to edges and disturbance suggests a dynamic ecological mosaic capable of supporting natural regeneration processes. These results

support the role of peri-urban forests as biodiversity refuges and providers of ecosystem services such as food provision, microclimatic regulation and wildlife habitat, even under anthropogenic pressure (Livesley et al. 2016). For this reason, the La Claridad forest emerges as a key space for ecological resilience and biological connectivity within the urban matrix of Popayán.

The phenological evaluation of flowering and fruiting complements this interpretation because these processes sustain fundamental plant–animal interactions essential for ecosystem functioning and mutualistic networks amongst species (Bascompte and Jordano 2008). In tropical ecosystems, approximately 90 percent of woody plants depend on pollinators and dispersers to complete their reproductive cycle (Jordano 2000; Godoy et al. 2009; Ollerton 2017).

Marked variations were observed in the temporal occurrence of phenological events. This pattern was statistically significant for flowering, as evidenced by the Rayleigh test ($p < 0.001$) and a moderate seasonality index ($r = 0.347$), confirming a non-uniform temporal distribution of this phenophase and suggesting the presence of different reproductive strategies amongst species (Kruskal–Wallis, $p < 0.001$).

Flowering showed higher concentrations in March, April and September; the first two months being periods of higher precipitation, while September corresponds to a transition towards drier conditions. In contrast, fruiting was mainly concentrated in September; however, this phenophase did not exhibit significant seasonality (Rayleigh test, $p = 0.077$), which is consistent with its lower seasonality index ($r = 0.235$) and suggests a more homogeneous temporal distribution, observed during relatively drier periods. These temporal patterns may suggest a possible association between climatic variation and reproductive phenophases; however, no formal statistical analysis was conducted to evaluate this relationship.

This behaviour of phenophases appears to be consistent with the climatic regime characteristic of the Cauca Department, which exhibits a bimodal pattern typical of the Cauca River Basin, with two rainy periods (March–April–May and September–October–November) and two dry periods (December–January–February and June–July–August) (Mera and Soto 2024).

Overall, these results suggest that flowering may be associated with periods of greater water availability, whereas fruiting appeared to be more frequent during relatively drier conditions, potentially favouring dispersal and establishment processes. Phenological synchrony amongst species varied, with greater overlap during flowering and lower synchronisation during fruiting.

This pattern is consistent with what has been documented in tropical and high-Andean forests, where peaks in the concentration of reproductive phenological events—particularly flowering, which exhibits moderate seasonality—are commonly observed during transitions between dry and wet seasons and may be related to variations in irradiance and water availability (Schaik et al. 1993; Corredor-Londoño et al. 2020).

In contrast, Ordónez-Blanco and Parrado-Rosselli (2017) reported high phenological persistence, with flowering and fruiting events distributed throughout most of the year. This difference is noteworthy, considering that their study was also conducted in a high-Andean forest with a bimodal precipitation pattern; however, the greater homogeneity observed may be associated with more stable microclimatic conditions, lower levels of anthropogenic disturbance or differences in floristic composition.

The moderate phenological seasonality recorded in this study may reflect fragmentation and local variations in resource availability. Additionally, Neil et al. (2014) highlight that peri-urban environments introduce critical variables that can alter phenology, showing that urbanisation and the "urban heat island" effect tend to advance flowering phases in various species. Although the effect of land cover was not directly evaluated in this study, research in arid and tropical ecosystems suggests that urban land cover is strongly correlated with temperature and, consequently, with the duration and proportion of flowering in plants (Neil et al. 2009).

Similarly, Salamanca-Fonseca et al. (2024) demonstrated that, in peri-urban areas, landscape structure and fragmentation may influence phenology by altering the presence of pollinators and dispersers, leading to more irregular or restricted phenological responses.

Additionally, the absence of flowering and fruiting in some species may be associated with specific phenological strategies or non-annual reproductive cycles, as has been documented in Neotropical tree species, where phenological events are concentrated in particular years in response to specific climatic conditions (Newstrom et al. 1994; Wright and Calderón 2006). This decoupling may also be related to limitations in pollination, failures in fertilisation or the abortion of reproductive structures (Stephenson 1981; Knight et al. 2005). For example, it has been reported that páramo species such as *Puya nitida* and *Puya trianae* exhibit temporal separation in flowering and variation in reproductive activity, indicating that not all species flower simultaneously or continuously (Restrepo-Chica and Bonilla-Gómez 2017). Likewise, in high-Andean forests, epiphytic species such as *Tillandsia complanata* may maintain prolonged flowering periods, but with variations in the intensity and frequency of reproductive events over time (Jaramillo and Cavelier 1998).

These patterns suggest that, even at a local scale, reproductive activity can be irregular or discontinuous, depending on environmental conditions and species-specific strategies. This behaviour was also observed in the present study, where species such as *Xanthosoma* sp., *Ficus* sp. and most orchids (Stelis, Oncidium and Comparettia) did not exhibit flowering and/or fruiting during the sampling period. This pattern is consistent with what has been reported for the Orchidaceae family, in which reproduction is often highly variable and strongly dependent on pollination. Similar trends have been observed in groups such as Piperaceae and Rubiaceae, where the production of flowers and fruits may vary depending on the availability of dispersers and pollinators (Tremblay et al. 2004; Ordónez-Blanco and Parrado-Rosselli 2017).

Amongst the species with the greatest reproductive stability, *Vismia baccifera*, *Besleria solanoides* and *Psychotria carthagenensis* stood out because they maintained prolonged flowering and fruiting periods. These species provide constant resources (nectar and fruits) for pollinators and frugivores, which makes them key functional components for forest regeneration (Faria and Araujo 2016; Espinosa and López 2019). In particular, *V. baccifera* and species of *Palicourea* maintain mutualistic relationships with bees, wasps, bumblebees and butterflies (Espinosa and López 2019; Pérez-Barrales et al. 2025); by contrast, *Siparuna aspera* exhibits floral adaptations that attract Cecidomyiidae flies, which act as efficient pollinators (Feil 1992).

Fruiting, although more restricted, exhibited an ecologically relevant pattern, characterised by a relatively homogeneous temporal distribution throughout

the study period, with a lower concentration of events, but greater stability in fruit presence. According to Mendes et al. (2023), the temporal distribution of fruits determines resource availability for dispersers and, consequently, seedling recruitment. Complementarily, Levine and HilleRisLambers (2009) note that asynchrony in fruit maturation can reduce interspecific competition and promote co-existence through functional differentiation, a pattern also documented in tropical trophic networks (Blüthgen et al. 2007; Chama et al. 2013). In the present study, the persistence of fruiting species during dry months suggests a strategic food supply for birds and bats, which are key organisms for dispersal and natural regeneration (Bascompte and Jordano 2008).

From a methodological perspective, this study provides evidence of the usefulness of qualitative phenological records in detecting temporal trends in small-scale plant communities. The combination of periodic sampling with presence and absence analysis enabled the detection of temporal variation without requiring large sample sizes, an important advantage for fragmented and difficult-to-access ecosystems. This approach aligns with recommended strategies for ecological monitoring in urban and peri-urban landscapes, where replicability and observation frequency are more informative than absolute density (Mohanta et al. 2024; Yin et al. 2024).

These results highlight the importance of continuing community-level phenological research in the Colombian Andes. Although there are studies focused on particular species such as *Ceroxylon quindiuense* (Martinez et al. 2021), species of Anthurium (Cano and Hernández 2024) and various orchids (Ordónez-Blanco and Parrado-Rosselli 2017), efforts integrating the reproductive dynamics of entire plant communities and their relationship to succession and resilience remain scarce. Advancing this line of research will enable assessment of the adaptive responses of plant communities to climate change and provide scientific inputs for planning ecological restoration strategies and conserving native flora in Andean peri-urban environments.

Conclusions

The floristic inventory conducted in the peri-urban forest of La Claridad revealed a diverse and structured plant composition. The prominent presence of families, such as Orchidaceae, Rubiaceae and Araceae, may reflect processes associated with vegetation regeneration and re-affirms the role of peri-urban systems as biodiversity reservoirs in landscapes subjected to anthropogenic pressure.

The qualitative phenological analysis suggested that flowering and fruiting patterns may be associated with climatic seasonality and habitat fragmentation, reflecting diverse reproductive strategies that promote co-existence and community stability. Species such as *Vismia baccifera*, *Besleria solanoides* and *Psychotria carthagenensis* stood out because they maintained prolonged flowering and fruiting periods and played an essential role in the continuous provision of resources for pollinators and dispersers, as well as in natural forest regeneration.

Overall, the results suggest that peri-urban forests are not passive remnants, but functional ecosystems that maintain vital ecological processes, contribute to biological connectivity and provide essential ecosystem services for the resilience of Andean landscapes. This study provides a baseline for understanding successional and reproductive dynamics in these systems and

demonstrates the usefulness of floristic and phenological inventories as tools for management, restoration, and conservation.

Continued phenological monitoring is recommended through multi-year studies that integrate climatic variables and quantification of plant–animal interactions in order to evaluate the adaptive responses of flora to climate change. Conserving and restoring these Andean peri-urban ecosystems should be a priority in territorial planning, recognising their role as ecological bridges that connect nature with the city and ensure long-term sustainability.

Recommendations

Although this study did not include structural forest data such as density, canopy cover or diameter at breast height (DBH), it is recommended that future floristic inventories in the area incorporate these types of variables because they allow quantification of ecosystem maturity, regeneration and structural complexity.

Long-term phenological monitoring is also recommended in this and other peri-urban forest fragments, integrating climatic variables and data on the abundance of pollinating and frugivorous fauna, in order to identify trends associated with climate change and landscape fragmentation. Furthermore, it is essential to strengthen conservation and restoration strategies, based on species with high phenological stability, which help maintain resource flow and ecological functionality in these ecosystems.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Artificial Intelligence (AI) use

The authors accept full responsibility for the content of the manuscript, including the disclosure of any use of AI.
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Author contributions

Natalia Majin-Quiñonez and Shirly Luligo-Miranda participated in the design and development of the research, conducted field data collection, performed the data analysis and prepared the initial draft of the manuscript. Giselle Zambrano-Gonzales and Jorge Becoche-Mosquera carried out the critical review and final editing of the document, providing observations to improve the structure and clarity of the text.

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Data availability

All of the data that support the findings of this study are available in the main text.