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Reproductive phenology of two co-occurring Neotropical mountain grasslands

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Abstract:

Aim: Climate tends to explain phenological variations in tropical ecosystems. However, water availability and nutrient content in soil strongly affect plant communities, especially those on old, climatically-buffered, infertile landscapes (OCBILs), and may impact these ecosystems' plant reproductive phenology over time. Here, we compare the reproductive phenology of sandy and stony tropical mountain grasslands, two co-occurring herbaceous communities of the *campo rupestre* OCBILs. We asked whether flowering, fruiting and dispersion are seasonal in both grasslands, and whether these phenophases differ due to variation in soil properties. We also asked whether the phenological strategies and the numbers of flowers and fruits differ between these two grasslands as soil conditions vary.

Location: Serra do Cipó, Minas Gerais, Brazil.

Methods: The phenology of herbaceous species of sandy and stony grasslands was monitored monthly over two consecutive years.

Results: Sandy and stony grasslands flowered and fruited all year long. We did not find a distinctive seasonal pattern at the community level of either studied grassland. However, flowering, fruiting and dissemination occurred in stony grasslands mainly during the rainy season, while sandy grassland species flowered in both seasons and fruited and disseminated mainly during the dry season, as observed in other Cerrado savanna vegetations. Flower and fruit production was higher in sandy grasslands than in stony grasslands, which may be linked to higher water retention in sandy grassland soils. In both communities, species of Cyperaceae, Eriocaulaceae and Xyridaceae contributed the most to overall production, whereas Poaceae and Velloziaceae, two important families in *campo rupestre*, barely participated in the reproductive phenology during our two-year survey.

Conclusions: Despite a strong seasonal climate, there was no reproductive seasonal pattern at the community level in *campo rupestre*. This first investigation of Neotropical grassland phenology indicates that the differential soil content may constrain the grasslands' reproductive phenology and restrict reproduction of stony grassland species to the most favorable season. Further studies of grassland phenology are necessary to disentangle the relative importance of soil, climate and other triggers, especially fire.

Keywords: Circular statistics, dissemination, flowering, fruiting, phenological strategy, rupestrian grassland, seasonality, savanna.

Nomenclature: Brazilian Flora 2020 in construction. Rio de Janeiro Botanical Garden. Available at: < <http://floradobrasil.jbrj.gov.br/> >. Accessed on: 04 Sep. 2017

Running head: Reproductive phenology of neotropical grasslands

Introduction

Plant phenology studies recurrent reproductive events such as flower budding, flowering, fruiting, and seed germination, as well as vegetative events like leaf flushing and shedding. These events link different groups within a community, such as decomposers, herbivores, pollinators, or seed dispersers (Morellato et al. 2016). Climate is the main factor controlling the timing of phenological events in plants, especially in seasonal environments (Rathcke & Lacey 1985; Fenner 1998; Ramirez 2002; Morellato et al. 2013), where the dry season limits the time available for growth, seed maturation and germination, and may decrease the diversity of phenological strategies in plant communities (Sarmiento & Monasterio 1983; Seghieri et al. 1995; Ramirez 2002; Batalha & Martins 2004).

Few studies have addressed the reproductive phenology of Neotropical grasslands, and the effect of climate seasonality on savanna and grassland phenology is yet to be demonstrated (Morellato et al. 2013; but see Rocha et al. 2016). In the Brazilian Cerrado savanna, most herbaceous species flower late in the wet season; conversely, in Brazilian and Venezuelan woody savannas, flowering occurs during the dry season (Monasterio & Sarmiento 1976; Ramirez 2002; Batalha & Martins 2004; Tannus et al. 2006). Besides the presence of a dry season, soil characteristics, such as water retention capacity or soil texture, are important determinants of the vegetation structure of old growth tropical grasslands (Veldman et al. 2015; Silveira et al. 2016). However, the relevance of soil as an environmental factor affecting plant species phenology is still poorly understood (but see Borchert 1994; Cardoso et al. 2012). Moreover, to our knowledge, no study has yet assessed whether soil type can affect plant phenology in tropical grasslands. Phenology defines the temporal structure of a community, including plant life cycles and interactions between plants and animals. Therefore, understanding how the environment (i.e. climate and soil conditions) affects and/or modifies phenology is fundamental, with applications that can improve management actions and guide conservation practices and restoration strategies (Andersen et al. 2005; Morellato et al. 2016; Buisson et al. 2017).

Old-growth grasslands are species-rich ecosystems that developed over many centuries. Among these old-growth grasslands are the Brazilian “*campo rupestre*” (or rupestrian grasslands), which are fire-prone mountain grasslands within the Cerrado domain (Silva & Bates 2002) and are regarded as OCBILs (old, climatically-buffered, infertile landscapes) (Silveira et al. 2016). The *campo rupestre* sustains a highly diverse vegetation composed of numerous endemic species (Giulietti et al. 1997; Fernandes 2016; Silveira et al. 2016). We focused our study on the mosaic of co-occurring stony and sandy grasslands (Le Stradic et al. 2015, see also Appendix S1) and the dominant herbaceous plant communities in *campo rupestre*

(Le Stradic et al. 2015). Under the same climate, soil condition and water availability are thought to play a major role as environmental filters that favor stress-tolerant species in both of these grasslands (Negreiros et al. 2014). Stony grasslands are often located on slopes and have coarser soil, lower water retention and higher mineral nutrient concentration. Sandy grasslands are located in flatter areas, and soils present higher water retention and lower mineral nutrient concentration (Le Stradic et al. 2015). Each grassland soil's distinct properties result in the filtering of distinct functional trait values (Negreiros et al. 2014). In contrast to sandy grasslands, the plants in stony grasslands present narrower leaves, higher stress tolerance, lower competitiveness and higher sclerophylly, which are all traits associated with drier soil conditions related to lower water retention. Therefore, we hypothesize that the phenological strategies and flower and fruit production should also differ between the two grasslands.

Here, we examine co-occurring herbaceous communities of stony and sandy grasslands under the same climate to determine whether their reproductive phenology varies due to different soil structure and composition. We address the following questions: (i) Do the plant communities of these two mountain grasslands present seasonal reproductive (flower, fruit, dispersion) phenological patterns? Do the phenological patterns differ between grassland types? To assess the seasonality of the two grasslands, we applied circular analysis as proposed by Morellato et al. (2010). We expected reproductive patterns to be seasonal, with a flower peak during the rainy season and a fruiting peak towards the end of the rainy season. This strategy has been observed in other grasslands and savannas under tropical seasonal climate. (ii) Do the phenological strategies differ between stony and sandy grasslands? To define the phenological strategies of each plant species, we considered frequency, duration, timing and amplitude (Newstrom et al. 1994) of three phenophases: flowering, fruiting and dissemination. We expected stony grassland communities to present short to medium seasonal flowering and fruiting strategies restricted to the rainy season due to lower water retention in soils, while sandy grassland would show a larger suite of reproductive strategies, as its soil presents higher water retention throughout the year. Finally, to precisely evaluate the differences in phenological response between these two grasslands, we assessed not only the phenological strategies but also the flower and fruit production, addressing the question: (iii) Do the numbers of flowers and fruits produced differ between the two grassland types? The harsher soil conditions should limit flower and fruit production in stony grasslands, so we expected flower and fruit production to be higher in sandy grasslands.

Material & Methods

Study area

Our study area is located in southeastern Brazil, in the southern portion of the Espinhaço Mountain Range, within the Morro da Pedreira Environmental Protection Area, a buffer zone of the Serra do Cipó National Park (state of Minas Gerais). *Campo rupestre* is the main vegetation formation in the Espinhaço Mountains (Silveira et al. 2016). The climate is seasonal, with a cold dry season from April to September and a warm rainy season from October to March (Appendix S1). The mean annual precipitation is 1,622 mm, and the mean annual temperature is 21.2 °C (Madeira & Fernandes 1999). We observed transitional seasons between the two main seasons, from dry to rainy and from rainy to dry, defined as September-October and March-April, respectively (Appendix S1).

Sandy and stony grasslands of *campo rupestre* are species-rich vegetations dominated by Poaceae, Cyperaceae, Xyridaceae, Eriocaulaceae and some Velloziaceae, as well as forb and sub-shrub species belonging to Asteraceae or Melastomataceae. Stony grasslands are characterized by the presence of *Vellozia* spp., which are strongly associated with dry

environments (Porembski & Barthlott 2000). In sandy grasslands, Poaceae and Cyperaceae are predominant (Appendix S2, Le Stradic et al. 2015). The soil in stony grasslands is coarser, with a high density of quartzic stones, and retains less water than sandy grassland soil (Le Stradic et al. 2015). The total N, P, K, Ca²⁺, Mg²⁺ concentrations and C_{org} content are significantly higher, and the soil more acidic, in stony grasslands than in sandy grasslands. In both grasslands, P and C_{org} content and pH vary seasonally: during the dry season, P concentrations are significantly higher, while C_{org} contents and pH are significantly lower (Le Stradic et al. 2015). Fire is a driver of vegetation dynamics in *campo rupestre*. In the study area, fires usually occur during the transition from dry to rainy season (September-October), with low to moderate fire frequency (Figueira et al. 2016, Alvarado et al. 2017).

Plant survey

To study the phenological patterns of the two main types of *campo rupestre* grassland, we selected five locations containing each of the two types, totaling 10 grassland sites: 5 sandy and 5 stony. Each pair of grasslands were less than 100 m apart. Each location covered between 0.23 ha to 2.36 ha; lay between 1,091 m and 1,310 m altitude; presented slopes between 4% to 17%; had a different fire history; and was not grazed (Appendix S3). Together, the 10 sites spread over an area covering around 560 ha of *campo rupestre*. At each of these ten sites, we randomly set up 10 permanent quadrats of 1 m² each, totaling 100 permanent quadrats (50 on sandy grasslands and 50 on stony grasslands). A detailed floristic survey was carried out in these 10 sites in 2009 (Le Stradic et al. 2015), and the phenological survey was performed monthly in the same quadrats, during two consecutive years, from November 2009 to October 2011. For each quadrat, we recorded all species, and for each species we counted (1) the total number of individuals or clumps (i.e. cluster of the same species, probably clones) and (2) the number of all reproductive stems in each phenophase (i.e. observable stage or phase in the annual life cycle of a plant): (i) flower (including flower buds and open flowers); (ii) fruit (including unripe and ripe fruits); and (iii) dissemination (open fruits with seed dispersal, or empty fruits following a month with fruit production). Thereafter, the number of reproductive stems presenting flowers, fruits or dissemination signs were designated by number of flowers, number of fruits and number of dissemination signs, respectively.

Phenological strategy analysis

We adapted the classification of Newstrom et al. (1994)—which considers frequency, timing, amplitude (numbers of flowers, fruits, and dissemination signs), and the duration of each phenophase—to describe and classify the phenological strategies of each species occurring on sandy and stony grasslands. We classified each species' phenology according to five phenological strategies (adapted from Newstrom et al. 1994): Continuous (C), phenological events present continuously over the year; Irregular/episodic (I), irregular phenological events over the year; Short (SS), phenophase lasting up to two months; Medium (SM), phenophase lasting from two to six months; Extended (SE), phenophase lasting more than six months but less than one year (Appendix S4). SS, SM and SE are seasonal strategies. For each species, we defined three periods of occurrence for each phenological strategy: (R) or rainy season (from October to March), (D) or dry season (from April to September), and (T) or the dry-to-rainy and rainy-to-dry transitional seasons, as defined above.

Flower and fruit production

For each grassland type, all reproductive stems with flower or fruit in each quadrat, hereafter referred to as flower and fruit production, were counted and further analyzed for the seven most important families in our grasslands, according to the survey performed by Le Stradic (2015): Asteraceae, Cyperaceae, Eriocaulaceae, Melastomataceae, Poaceae,

Velloziaceae and Xyridaceae. The remaining species were classified as other forbs or other subshrubs, because the families were represented by few species.

Statistical analyses

To characterize the seasonality of flowering, fruiting and dissemination in stony and sandy grasslands, we applied circular statistical analyses as described by Morellato et al. (2010), using the total number of species at the peak of flowering, fruiting and dissemination per month. For each phenophase, the number of species exhibiting a given phenological event on the peak date (i.e. the date when the highest number of flowers, fruits or dissemination signs was observed) of each month was treated as a circular frequency distribution, with data grouped at 30° intervals (30° = interval between two months) and January as the starting point (15°). The mean angle μ represents the mean date of the flowering, fruiting or dissemination period, and r is the measure of the concentration of the circular distribution of frequencies around the mean angle. Values of r range from 0 (when data are completely dispersed in all angles) to 1 (when all the data are concentrated around one angle or date) (Zar 1996). The Rayleigh test (i.e. test of non-uniformity) assesses the null hypothesis, i.e. there is no sample mean direction of a set of points on a circle. A significant Rayleigh test indicates a significant mean angle or mean date. When species are concentrated around the mean angle or date, the phenological pattern is seasonal (Morellato et al. 2010). We could not compare significant mean angles or seasonal phenological patterns between sandy and stony grasslands, because a significant mean angle was never present for both grasslands for the same phenological event. Circular analyses were performed using the software Oriana 3.0 (Kovach Computing Services 2012).

To describe the different phenological strategies encountered in *campo rupestre*, the numbers of species associated with each strategy (i.e. Continuous, Irregular, Seasonal Short, Seasonal Medium and Seasonal Extended) were analyzed using permutation tests performed in R package «coin» (Zeileis et al. 2008). Permutation tests are a type of statistical significance test that obtains the population distribution by calculating the sample statistics under every possible permutation of the observed data points. The calculated statistic of the permutation tests is z when one explanatory variable is tested, or $\max T$ when two or three explanatory variables are tested.

To analyze flower and fruit production at each site, according to the grassland type and plant families, GLM procedures were performed assuming a Poisson distribution and a logarithmic link function. The numbers of flowers and fruits were the response variables, while grassland types and families were the categorical variables (Crawley 2007).

These analyses were performed with R version 3.2 (R Core Team. 2015. R: A language and environment for statistical computing. Vienna, Austria).

Results

We recorded 146 species in sandy grasslands and 155 species in stony grasslands, mainly perennial species (138 species or 94.5% in the stony grasslands, and 151 species or 97.4% in the sandy grasslands, Table 1, Appendix S5). In stony and sandy grasslands, 26.7% and 34.1% of species, respectively, did not reproduce during the observation period (Table 1, Appendix S6).

Seasonality of flowering, fruiting and dissemination on stony and sandy grasslands.

Stony and sandy grasslands presented species flowering, fruiting and disseminating all year long, with few variations between seasons (Fig. 1, Appendix S1). Sandy grasslands presented

a significant seasonal mean flowering peak date in March ($Z=5.53$, $p<0.01$) and a seasonal mean fruiting peak date in May ($Z=4.71$, $p<0.01$), but both r scores were low (0.26 and 0.24, respectively, Fig. 1 a and c; Appendix S7), indicating a very low seasonality. Dissemination time did not show a significant mean peak date (μ) or seasonality (Fig. 1 e, Appendix S7). Stony grasslands did not show a significant seasonality for flowering or fruiting (Fig. 1 b, d, Appendix S7) and showed only marginally significant mean dissemination peak dates in December ($Z=3.26$, $p<0.05$, with $r=0.19$, Fig. 1 f, Appendix S7), also due to a barely unimodal distribution, though peak activity intensified during the wet season for the three phenophases (Fig. 1 b, d, f).

Phenological strategies in stony and sandy grasslands

Sandy and stony grasslands showed no significant differences regarding the proportion of phenological strategies for either flowering, fruiting or dissemination (Table 2). For all phenophases, in both grasslands, less than 20% of species presented continuous or irregular strategies (Table 2, Appendix S4 a, b), and over 80% of species showed seasonal strategies. In both grasslands, about 80% of species showed seasonal short (SS, Appendix S4 c, d) to seasonal medium (SM, Appendix S4 e, f) flowering strategies, while around 60% of species presented seasonal medium (SM) to seasonal extended (SE, Appendix S4 g, h) fruiting strategies (Table 2). There was no significant difference among the three seasonal fruiting strategies in stony grasslands (Table 2). For dissemination, between 82% and 79% of species had an SS or SM strategy in both grasslands (Table 2).

SS species in both grasslands flowered and fruited mainly during the rainy season. SM species in sandy grasslands flowered primarily during the dry season, but those in stony grasslands flowered during both rainy and dry seasons (Fig. 2, Appendix S8). A large share of species presented an SM fruiting strategy, occurring mostly during the dry season in sandy grasslands, but in stony grasslands during the rainy season (Fig. 2, Appendix S8). Seasonal extended (SE) species of both grasslands fruited during the dry season (Fig 2, Appendix S8). SS species in sandy grasslands disseminated during both rainy and dry seasons, while SS species in stony grasslands disseminated mainly in the rainy season (Fig. 2, Appendix S8). Conversely, SM species in sandy grassland disseminated mostly in the dry season, while stony grasslands species disseminated in both seasons (Fig. 2, Appendix S8); some SM species disseminated also during the transitional seasons (Fig. 2, Appendix S8). SE species in both sandy and stony grasslands disseminated in the dry season (Fig. 2, Appendix S8).

Flower and fruit production

The mean numbers of flowers and fruits produced per site were significantly higher in sandy than in stony grasslands (227.7 ± 26.6 flowers/10 m² and 211.6 ± 12.48 flowers/10 m² respectively, $z=-2.42$ $p=0.01$; 532.6 ± 45.9 fruits/10 m² and 464.8 ± 47.5 fruits/10 m², respectively, $z=-6.78$ $p<0.001$). Cyperaceae, Xyridaceae and Eriocaulaceae produced the largest numbers of flowers and fruits in both grasslands (Table 3). Poaceae presented the highest number of species in both grasslands but produced few seeds (Table 3). Asteraceae, Velloziaceae, Xyridaceae and other sub-shrubs had higher flower and fruit production in stony grasslands, while Cyperaceae, Poaceae, and other forbs had higher flower and fruit production in sandy grasslands (Table 3).

Discussion:

Although *campo rupestre* is characterized by a strong seasonal climate, our results did not show the expected distinct reproductive seasonal patterns at the community level. Both grasslands produced flowers and fruits all year long (see also Rocha et al. 2016). We observed only very low seasonality, and then only for the sandy grasslands. Most studies show that

climate seasonality influences tropical grassland phenology, triggering the flowering of herbaceous species during mid to late rainy season (Batalha & Martins 2004; Tannus et al. 2006). We did not find the expected differences in the proportions of phenological strategies between stony and sandy grasslands. Despite the lack of seasonality at the community level, most species in both grassland types present seasonal strategies, whereas only small portions present continuous and irregular phenological strategies.

Most species in both grasslands presented a short flowering peak during the rainy season, as found in other seasonal grassland ecosystems in Venezuela and Cameroon (Monasterio & Sarmiento 1976; Seghieri et al. 1995; Ramirez 2002) and in the Brazilian Cerrado (Batalha & Martins 2004; Tannus et al. 2006; Munhoz & Felfili 2007). This phenological pattern is often related to the rainy season's higher water availability and the following dry season's acute water shortage, which are characteristic of a seasonal system. Available water is crucial for herbs to complete their vegetative growth and accumulate the carbohydrates that enable them to flower (Sarmiento & Monasterio 1983; Ramirez 2002; Batalha & Martins 2004). In the studied sandy grasslands, flowering also occurred during the dry season, probably because sandy grassland soils retain more water than the coarser stony grassland soils. Biotic factors may also play an influential role in the reproductive phenology of the studied grasslands. Most species had short or medium seasonal flowering strategies, indicating that the specific flowering period coincides with not only the best environmental conditions, but also the availability of biotic resources such as pollinators (Guerra et al. 2016; Brito et al. 2017). The need for specific pollinators such as large bees, wasps and/or dipterans (most active during the dry season) may favor a dry seasonal medium strategy (Freitas & Sazima 2006, Carstensem et al, 2014, Appendix S2).

Phenological fruiting strategies differed between the two grasslands. In sandy grasslands, fruiting occurred mainly during the dry season, with a higher number of species disseminating during the dry and transitional seasons. Most species that fruited during the dry season adopted an SM or SE fruiting strategy, depending on the time required for fruit maturation and seed dispersal. Long fruiting seasons are already described for Cerrado herbaceous and sub-shrub species: anemochoric and autochoric species produce and disseminate fruits during the dry season, whereas zoochorous species do so most during the rainy season (Batalha & Martins 2004; Munhoz & Felfili 2007; Camargo et al. 2013). In *campo rupestre*, anemochory and autochory are the two main seed dispersal syndromes (Conceição et al. 2007; Dutra et al. 2009). The end of the dry season is marked by stronger and more frequent winds (Fernandes 2016) and is therefore the optimal period for fruit and seed dissemination. In stony grasslands, more species produced fruits and disseminated during the rainy season than the dry season, possibly related to seed dispersal by water and/or more favorable conditions for germination (Silveira et al. 2012). No study has reported hydrochory (but see Trovó & Stützel 2011; Goldenberg et al. 2015), but the importance of water as a dispersal mechanism in *campo rupestre* should not be underestimated: sandy grasslands are regularly flooded during the rainy season, and sedge seeds are known to be buoyant (Leck & Schütz 2005).

Our results highlighted significant differences in flower and fruit production between sandy and stony grasslands, with the expected higher flower and fruit production in sandy grasslands. These differences may be explained by low water availability in stony compared to sandy grasslands, but this hypothesis needs to be experimentally tested. In both grasslands, all flowers and fruits were produced by around 10% of individuals from a limited number of species. Cyperaceae, Eriocaulaceae and Xyridaceae species produced most of the flowers and fruits in both grasslands, whereas important and species-rich families of *campo rupestre*, such as Poaceae and Velloziaceaea (Le Stradic et al. 2015), barely reproduced during our two-year

phenological survey (see also Neves & Damasceno-Junior 2011). While this can be explained as an irregular reproductive event (i.e. does not occur every year), we suggest that, as the *campo rupestre* is a fire-prone environment, numerous species are resprouters (Le Stradic et al. 2015; Le Stradic et al. 2017) and need fire as a stimulus to induce flowering and fruiting (Munhoz & Felfili 2007; Conceição et al. 2013). Such a strategy would allow them to avoid years of sub-optimal climate and expend more resources in optimal years (Venable 2007). Some studies have pointed out that recurrent burnings are not favorable for sexual reproduction because it reduces seed supply, even for species occurring in tropical fire-prone environments; consequently, vegetative reproduction may increase under frequent fire regimes (Hoffmann 1998; Setterfield 2002), such as in *campo rupestre* (see Furley & Ratter 1988).

This is the first quantitative study examining the phenology of *campo rupestre* herbaceous flora. Understanding variations in reproductive strategies requires further studies of grassland phenology, and long-term phenology monitoring would better assess climate influences on tropical mountain grasslands. To better comprehend the dynamics of fire-prone tropical grasslands, future phenology studies should focus on patterns of flower and fruit production driven by fire regimes. The small proportion of individuals participating in the phenology of both grasslands implies a slow succession process, a potential limitation on the natural regeneration of *campo rupestre* after strong disturbances, and a low capacity for colonization of degraded areas by *campo rupestre* species. Hence, we must learn more about limited seed source and the lack of clear phenology and reproductive strategies for producing quality seeds, a strong constraint on the conservation and ecological restoration of *campo rupestre* (Le Stradic et al. 2014; Buisson et al. 2017).

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Table 1. Total numbers and percentages (%) of species surveyed in the sandy and stony grasslands at Serra do Cipó (Minas Gerais, Brazil), classified as perennial and annual species and as presenting at least one or no reproductive events during the study (flower, fruit and/or dissemination).

	Sandy grasslands		Stony grasslands	
	Number of species	Number of individuals	Number of species	Number of individuals
Perennial	138 (94.5%)	29 100	151 (97.4%)	31 327
Annual	8 (5.5%)	127	4 (2.6%)	27
with reproductive event	107 (73.3%)	2,691 (9.2%)	89 (65.9%)	2,226 (7.1%)
without reproductive event	39 (26.7%)	26,409 (90.8%)	46 (34.1%)	29,101 (92.9%)
Total	146	29 227	155	31 354

Table 2. Distribution of species of sandy and stony grasslands, at Serra do Cipó (Minas Gerais, Brazil), according to the phenological strategies for phenological event and grassland type. Mean number (\pm standard error) of species and percentage of species (indicated in brackets) for each strategy, according to the total number of species for each grassland type. Phenological strategies: Continuous (C), Irregular (I), Seasonal Short (SS), Seasonal Medium (SM), Seasonal Extended (SE). For each phenological event, permutation tests were performed within each grassland type to compare occurrence of phenological strategies therein (maxT test). Letters indicate significant differences between strategies within each grassland type. Permutation tests were performed between grassland type (Z tests); * means p-value $P < 0.05$, otherwise tests were not significant.

	Strategies	Sandy grasslands	Stony grasslands	
Flowering	C	2.0 ± 0.4^a (4 %)	3.0 ± 0.3^a (7 %)	
	I	3.8 ± 0.7^a (8 %)	3.4 ± 0.7^a (8 %)	
	SS	20.0 ± 0.9^b (40 %)	19.6 ± 1.4^b (43 %)	
	SM	20.2 ± 1.6^b (40 %)	17.0 ± 2.3^b (37 %)	
	SE	4.0 ± 0.3^c (8 %)	2.2 ± 0.4^a (5 %)	*
	Permutation tests - differences between strategies	maxT = 2.96, p = 0.016	maxT = 3.23, p = 0.006	
Fruiting	C	3.0 ± 0.4^a (7 %)	3.8 ± 0.4^a (9 %)	
	I	2.4 ± 0.5^a (5 %)	3.4 ± 0.7^a (9 %)	
	SS	9.6 ± 0.5^b (21 %)	9.4 ± 1.3^b (22 %)	
	SM	16.8 ± 0.7^c (36 %)	14.2 ± 1.8^b (33 %)	
	SE	14.2 ± 1.4^c (31 %)	11.2 ± 1.2^b (27 %)	
	Permutation tests - differences between strategies	maxT = 3.10, p = 0.002	maxT = 2.95, p = 0.01	
Dissemination	C	-	-	
	I	3.2 ± 0.6^a (7 %)	2.6 ± 0.5^a (6 %)	
	SS	20.6 ± 0.9^b (42 %)	12.4 ± 1.5^b (28 %)	*
	SM	19.8 ± 1.4^b (40 %)	22.8 ± 1.8^c (51 %)	
	SE	5.6 ± 0.4^c (11 %)	6.4 ± 0.6^d (15 %)	
	Permutation tests - differences between strategies	maxT = 2.81, p = 0.007	maxT = 3.68, p = 0.001	

Table 3. Flower and fruit production per site (i.e. average number of reproductive stems with flower or fruit per site and standard error), for the main families based on peak production, in sandy (Sa) and stony (St) grasslands at Serra do Cipó (Minas Gerais, Brazil). Results of the GLM procedures (family: Poisson, link: log) are indicated. Letters indicate significant differences between families among grassland types.

	Mean number of reproducing species / site		Flower production					Fruit production				
	Sa	St	Sa		St		GLM procedures	Sa		St		GLM procedures
Asteraceae	3.4 ± 1.2	3.2 ± 0.4	7.6 ± 1.9	a	23.2 ± 8.4	a	8.44 ***	5.4 ± 1.5	a	8.7 ± 2.4	a	2.75 **
Cyperaceae	11.0 ± 0.4	10.6 ± 1.6	251.2 ± 25.6	b	158.1 ± 21.6	b	-14.42 ***	290.6 ± 29.6	b	170.8 ± 27.0	b	-17.43 ***
Eriocaulaceae	4.8 ± 0.5	5.6 ± 1.3	70.5 ± 14.8	c	68.9 ± 15.6	c	-0.42 ^{NS}	51.6 ± 12.5	c	49.1 ± 11.2	c	-0.78 ^{NS}
Other Forbs	9.4 ± 1.2	5.2 ± 1.4	22.5 ± 3.4	d	14 ± 3.2	d	-4.40 ***	8.5 ± 2.7	d	1.9 ± 0.5	d	-5.90 ***
Melastomataceae	2.4 ± 0.6	2.2 ± 0.5	20.2 ± 6.9	d	14 ± 5.9	d	-3.33 ***	33 ± 14.0	e	41.7 ± 15.4	e	3.17 ***
Poaceae	4.0 ± 0.6	4.4 ± 0.8	29.7 ± 6.7	e	14.8 ± 4.9	d	-6.92 ***	29.7 ± 8.8	e	9.1 ± 4.6	a	-9.87 ***
Other Sub-shrubs	4.0 ± 1.3	6.0 ± 0.5	13.1 ± 4.4	f	38.2 ± 14.8	e	10.57 ***	7.8 ± 2.1	d	37.9 ± 15.0	e	12.71 ***
Velloziaceae	0.8 ± 0.2	1.2 ± 0.4	0.5 ± 0.3	g	4.7 ± 3.7	f	4.76 ***	1.3 ± 0.6	f	11.9 ± 5.4	f	7.58 ***
Xyridaceae	11.0 ± 1.4	7.4 ± 1.8	157.2 ± 36.0	h	227.6 ± 28.1	g	11.28 ***	138.2 ± 31.3	g	177.6 ± 23.5	b	6.99 ***
GLM procedures			<i>p</i> >0.001		<i>p</i> >0.001			<i>p</i> >0.001		<i>p</i> >0.001		

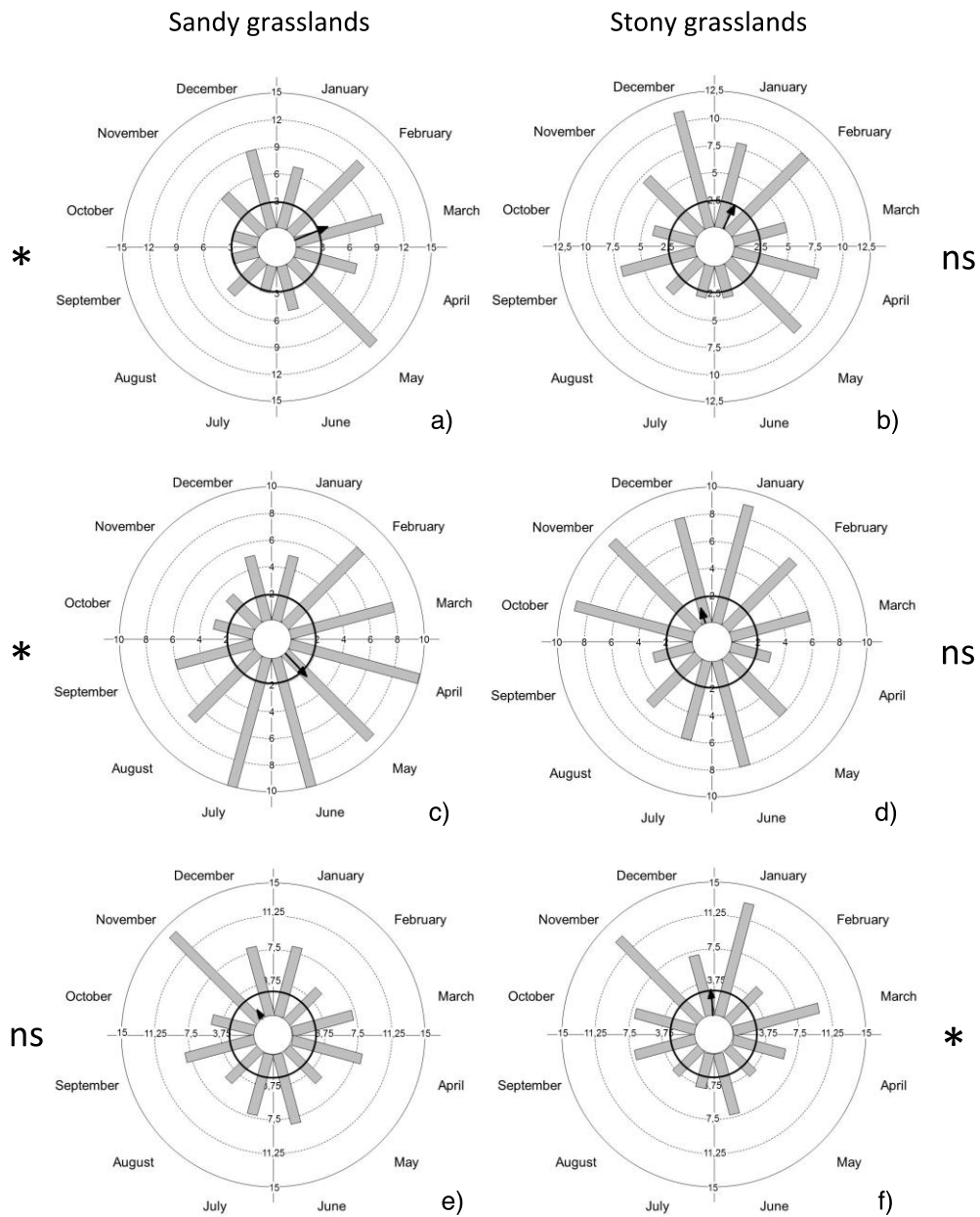


Fig. 1. Reproductive phenology of sandy (left) and stony (right) grasslands at Serra do Cipó (Minas Gerais, Brazil). Total monthly number of species at peak of flowering (a) (b), fruiting (c) (d), and dissemination (e) and (f) are presented. Arrows point to the mean date or mean angle (μ); the length of the arrow indicates the concentration around the mean, i.e. the degree of seasonality; and the black circle is the significant threshold. Results of Rayleigh test are indicated for each graphic: ns = non-significant and * = p value < 0.05. All results of statistical tests **are** available in Appendix S7

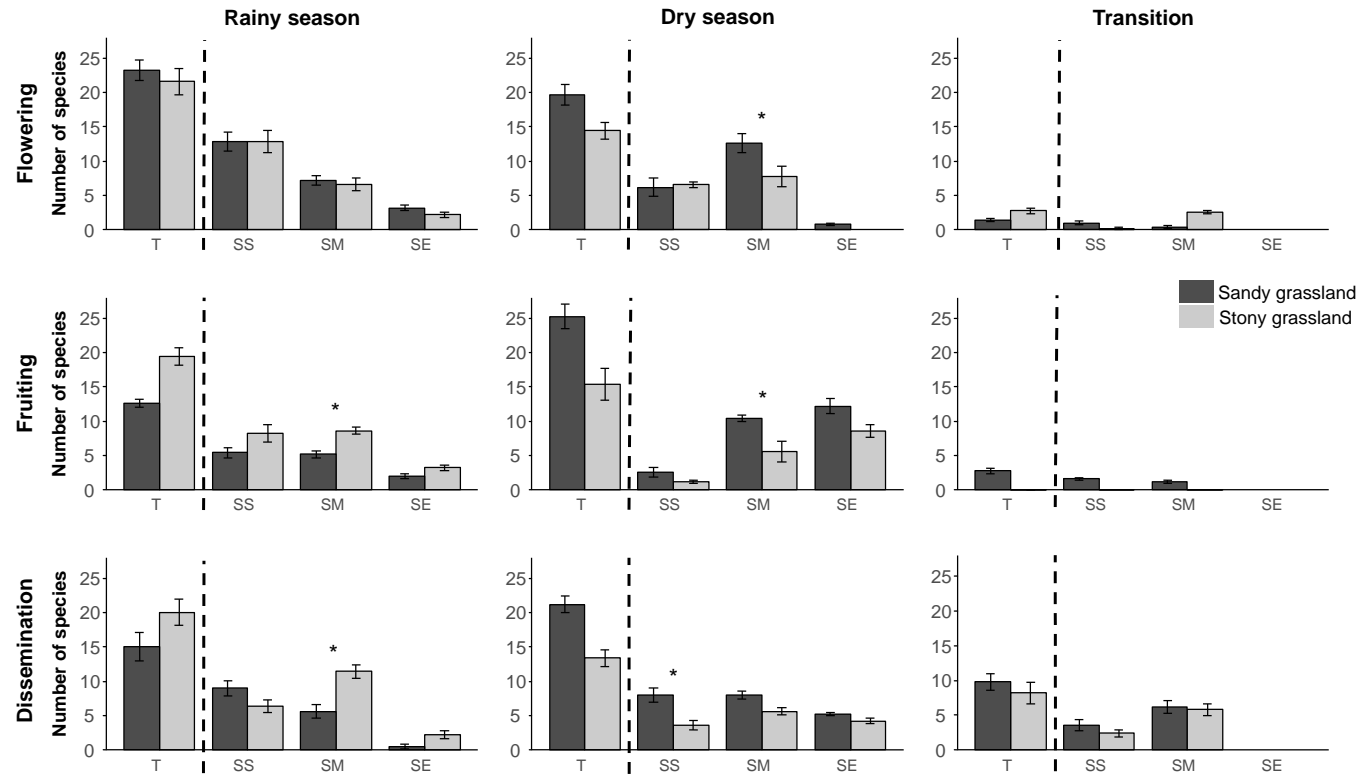


Fig. 2: Mean number of species per phenological event (flowering, fruiting, dissemination) according to the seasons—rainy season, dry season and transition—for the two grassland types: sandy grassland and stony grassland, at Serra do Cipó (Minas Gerais, Brazil). The total mean number of species (T) per phenological event is represented first and is then decomposed according to the three seasonal phenological strategies: Short (SS), Medium (SM), Extended (SE) seasonal strategy. * indicates significant difference with $p < 0.05$ between sandy and stony grasslands. A detailed table of all statistical test results is available in Appendix S8.

Supporting Information to the paper Le Stradic S. et al. Reproductive phenology of two co-occurring Neotropical mountain grasslands. *Journal of Vegetation Science*. Appendix S1. Distribution of the mean monthly temperatures (°C) at 6:00am and 1:00pm, and cumulative rainfall (mm). Mean percentage of species with flowers, fruits and dissemination, per site in sandy grasslands and stony grasslands, from November 2009 to October 2011 at Serra do Cipó, MG.

Supporting Information to the paper Le Stradic S. et al. Reproductive phenology of two co-occurring Neotropical mountain grasslands. *Journal of Vegetation Science*. Appendix S2. General view of *campo rupestre* at Serra do Cipó (Minas Gerais, Brazil), detailed pictures of sandy grasslands and stony grasslands, and pictures of some *campo rupestre* species from the most common families.

Supporting Information to the paper Le Stradic S. et al. Reproductive phenology of two co-occurring Neotropical mountain grasslands. *Journal of Vegetation Science*. Appendix S3. Main characteristics of each study site.

Supporting Information to the paper Le Stradic S. et al. Reproductive phenology of two co-occurring Neotropical mountain grasslands. *Journal of Vegetation Science*. Appendix S4. Examples illustrating the phenological strategies used in this study for some selected species occurring in sandy grasslands and stony grasslands at Serra do Cipó (Minas Gerais, Brazil).

Supporting Information to the paper Le Stradic S. et al. Reproductive phenology of two co-occurring Neotropical mountain grasslands. *Journal of Vegetation Science*. Appendix S5. List of species surveyed in the sandy and stony grasslands at Serra do Cipó (Minas Gerais, Brazil), showing reproductive activity in the period of study, along with their habitat of occurrence, the phenological strategy and the reproductive timing.

Supporting Information to the paper Le Stradic S. et al. Reproductive phenology of two co-occurring Neotropical mountain grasslands. *Journal of Vegetation Science*. Appendix S6. List of species surveyed in the sandy and stony grasslands at Serra do Cipó Minas Gerais, Brazil, that did not show reproductive activity in the period of study, along with their habitat of occurrence.

Supporting Information to the paper Le Stradic S. et al. Reproductive phenology of two co-occurring Neotropical mountain grasslands. *Journal of Vegetation Science*. Appendix S7. Results of circular statistical analyses on the flowering, fruiting and dissemination phenology of sandy and stony plant communities at Serra do Cipó (Minas Gerais, Brazil).

Supporting Information to the paper Le Stradic S. et al. Reproductive phenology of two co-occurring Neotropical mountain grasslands. *Journal of Vegetation Science*. Appendix S8. Mean number of species per phenological event (flowering, fruiting, dissemination) and seasonal phenological strategy, according the grassland types and timing at Serra do Cipó (Minas Gerais, Brazil).