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Monitoring immediate post-fire vegetation dynamics of tropical mountain grasslands using phenocameras

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ABSTRACT

The growing incidence of uncontrolled wildfires all over the globe has called for urgent close monitoring of fire events, awareness, prevention, and management approaches. Phenocameras, ground sensors for monitoring plant phenology by taking sequential RGB digital images, can be an accessible and accurate tool for identifying, monitoring, and analyzing fire events and vegetation recovery. Here, we evaluated the application of an RGB camera system as a methodological approach to monitor and assess the post-fire recovery of a tropical mountain grasslands, the Brazilian *campo rupestre*. Using camera-derived vegetation indices, we investigated the immediate post-fire regrowth, and short-term post-fire leafing among four vegetation types: wet grassland, peatbog, stony grassland, and rocky outcrop. We recorded significant variations in the post-fire recovery among the grassy vegetation types. The results indicated that fire represents an important driver of leafing dynamics by shortening the length of post-fire growing seasons. The phenological metric of growing season length (GSL) indicated a full post-fire ecosystem recovery in the third year after the fire. The green-up index represented well the dynamics of post-fire vegetation regrowth and recovery across the landscape. Phenocameras rapidly detected fire occurrence and post-fire vegetation responses across vegetation types, demonstrating their significant application in the fire ecology of grassy ecosystems. The accessible, low-cost, and easy-to-setup camera system allows the application of near-remote phenology as a monitoring system and an indicator of vegetation recovery, which may improve restoration and management plans, promoting the conservation of the highly diverse *campo rupestre* grassland ecosystems.

1. Introduction

There is a growing incidence of uncontrolled wildfires in all major continents of the world, following heatwaves and droughts, or the path of deforestation, while the current trends are projected to continue increasing (Jolly et al., 2015; Dowdy et al., 2022, Strömberg and Carla Staver, 2022, Pimont et al., 2022). The awareness of the effects of fire on biodiversity, human health, and the economy has been rising, and more research into effective monitoring, prediction, prevention, and management approaches are called for (dos Santos et al., 2021; Dowdy et al., 2022; Giorgis et al., 2021; Khairoun et al., 2022; Moyo, 2022; Pivello et al., 2021; Strömberg and Carla Staver, 2022). On the other hand, fire plays a key role in several non-forested ecosystems. It interacts critically with plant phenology by influencing seed dormancy and plant community composition to the length of growth season, ecosystem productivity, and carbon cycling (Bond et al., 2005; Bowman et al., 2009; He et al., 2019; Pausas and Keeley, 2019). The increasing number of events, primarily the catastrophic ones, imposes a great challenge for the existing remote sensing phenological approaches to improve the refinement and monitoring needed to predict fire events and guide the

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management practices in both fire-prone and fire-sensitive ecosystems (Hantson et al., 2016; Khairoun et al., 2022; Morellato et al., 2016).

Land surface phenology (LSP) analysis, where phenological metrics are extracted from satellite-time series, has been demonstrated to be effective in tracking wildfires, with post-fire responses related to shifts in greenness metrics (Wang and Zhang, 2017, 2020). A robust analysis using daily 250-m MODIS time series shows that burn severity significantly decreased greenness rates, while timing metrics have varied responses according to burn severity and also to land surface properties (Wang & Zhang 2020). Satellite-derived indices, such as the Normalized Difference Vegetation Index (NDVI), are well consolidated for the monitoring of fire over spatial and temporal scales (Bastarrika et al., 2014; Giglio et al., 2010; Pereira, 2003; Roy et al., 2019). Nonetheless, in tropical grasslands, such as the open cerrado and *campo rupestr*e mountain grasslands, the fast plant recovery may impose a challenge to the ability of satellites to monitor immediate post-fire regrowth dynamics (Alves et al., 2022; Pereira, 2003). The low temporal resolution of satellite observations and atmospheric disturbances, such as cloud cover and smoke, may impact the reliability of the imagery information for post-fire evaluation (Sano et al., 2007), especially across tropical grasslands, despite the attempts to develop satellite-derived approaches to overcome these limitations (Alves et al., 2022).

Radar sensors have been demonstrated to be effective in monitoring post-fire vegetation dynamics, as backscattering microwave energy demonstrated to be sensitive to changes in vegetation structure, and because they can penetrate clouds (Balling et al., 2021; Chuvieco et al., 2019). Synthetic-Aperture Radar (SAR) offers high-spatial and medium-temporal resolution datasets and represents an alternative to complement the traditional optical remote sensing dataset, particularly over tropical areas where cloud-cover conditions are persistent (e.g., Balling et al., 2021; Siegert and Ruecker, 2000; Verhegghen et al., 2016). Yet, few studies have been conducted with radar sensors to track vegetation recovery after fire and most of them consider the monthly or yearly post-fire recovery time due to the medium-temporal resolution of the available data (Chhabra et al., 2022; Gitas et al., 2012; Jenkins et al., 2014; Minchella et al., 2009; Polychronaki et al., 2013). The use of combined local and global scales in the last years has increased, emphasizing the need to obtain fine-resolution information to validate and reduce uncertainties of global scale products (Chuvieco et al., 2020).

Therefore, a near-ground sensor, able to collect high temporal frequency information at a fine-scale resolution (hourly or daily) from the vegetation recovery, can improve our understanding of the ecological processes and shifts after a fire episode. The use of time-lapse images captured by digital cameras (phenocameras) in the field has been widely applied for vegetation monitoring, including in the tropics (e.g., Alberton et al., 2014, 2019; Lopes et al., 2016; Nagai et al., 2016). Phenocameras are reliable tools able to simultaneously monitor leaf phenology and track leaf exchange transitions at multiple sites, with reduced human sampling effort and a high temporal resolution (daily) of data collection (Alberton et al., 2017; Alberton et al., 2019; Crimmins and Crimmins, 2008). The near-surface remote system using ground cameras is a powerful tool to observe and detect shifts in vegetation structure, such as recovery from disturbance events of deforestation, fire, flooding, and species invasion (Alberton et al., 2017, 2019, 2023). We advocate that, through a set of daily photographs, it is possible to visualize the process of fire occurrence and immediate post-fire vegetation recovery, showing real-time vegetation regrowth responses, particularly in highly heterogeneous grassy landscapes (Alberton et al., 2017, 2019). Therefore, responses detected by phenocameras can likely help to take fast and appropriate conservation and management measures.

Here, we conducted a multi-site analysis to evaluate the application of an RGB-camera system for the monitoring and assessment of the immediate post-fire vegetation regrowth and short-term vegetation recovery across a tropical snow-free mountain grassland ecosystem. The Brazilian *campo rupestre* (rupestrian grassland) is a fire-prone (Figueira et al., 2016), highly diverse and heterogeneous tropical vegetation complex dominated by grasslands (Silveira et al., 2016). We used time series indices derived from the spectral information of digital cameras, aiming to answer the following research questions: (i) Are camera-derived vegetation indices a reliable methodological approach for the assessment of post-fire vegetation responses of tropical grasslands? and (ii) Are phenocameras able to systematically evaluate leafing transition changes after a fire episode across the grassland vegetation mosaic? We expect that the high temporal data frequency and fine-scale resolution of phenocameras monitoring will detect vegetation recovery dynamics of the different vegetation types and provide a systematic analysis of the ecosystem recovery through the assessment of leafing phenological transition dates of growing seasons.

2. Material and methods

2.1. Study sites

The study was conducted in the National Park of Serra do Cipó and its buffer zone, the Environmental Protection Area *Morro da Pedreira*, located at the Serra do Cipó, the southern portion of the Espinhaço range (19º 10′-20′ S and 43º 30′-40′ W), Minas Gerais, Southeastern Brazil (**Fig. S1**). The Southern part of the Espinhaço Mountain Range, largely represented by Serra do Cipó, occupies a transition zone between the Cerrado and the Atlantic Forest (Morellato and Silveira, 2018). The *campo rupestre* is an ancient mountaintop ecosystem occurring mostly over 900 m altitude above sea level (Fig. S1), composed of different types of herbaceous and shrubby vegetation growing side-by-side over shallow, quartzitic, acidic, and nutrient-poor soils (Mattos et al., 2019; Silveira et al., 2016). Characterized by a vegetation mosaic with a dominant grassland matrix, the unique heterogeneous landscape presents a high species diversity and elevated rates of endemism (Silveira et al., 2016; Le Stradic et al., 2018a; Morellato and Silveira, 2018, Mattos et al., 2019, Fernandes, 2016). The climate is classified as tropical altitudinal climate (Cwb) (Köppen, 1931), with warm and wet summers and cold and dry winters. The annual average temperature is 21.2 °C and the annual average rainfall is ca. 1622 mm (Le Stradic et al., 2018a). Rainfall distribution is seasonal, mainly concentrated during the rainy season from November to April (monthly rainfall >60 mm), while the dry season extends from May to October (monthly rainfall <60 mm, Alvarado et al., 2017, Stradic et al., 2018a).

We have monitored four *campo rupestre* sites distributed along the altitudinal gradient of Serra do Cipó, named as follows: Cedro (CE) (1101 m), Reserva Vellozia (RV) (1150 m), Pedra do Elefante (PE) (1255 m), and Quadrante 16 (Q16) (1303 m), (Mattos et al., 2019). The dominant vegetation types at CE, PE, and Q16 sites captured within the phenocameras imagery were recognized based on local surveys (Mattos et al., 2019; Rocha et al., 2016) to assess the main plant families and species. The RV vegetation types were identified by in situ inspection and by a quick comparative plant survey (Morellato et al., unpublished). We sampled the four dominant vegetation types of *campo rupestre* along the study sites (Mattos et al., 2019): wet grassland (Wg), stony grassland (Sg), rocky outcrop (Ro), and the peatbog (Pb).

2.2. Near-surface remote phenology: phenocameras setup for pre- and post-fire monitoring

The long-term, ongoing, near-surface phenological monitoring of *campo rupestre* at Serra do Cipó was set up in 2014, to survey the seasonal vegetation patterns across the landscape after a one-site pilot study that started in 2013. Besides accurately characterizing leaf phenological patterns, the monitoring of burned sites and vegetation recovery took crucial importance since camera deployment occurred just after an extensive fire event in October 2014 (**Fig. S2** and Fig. 1), affecting several of our long-term study sites (Silveira et al., 2019). A Mobotix Q24 and a PlantCam time-lapse camera were installed at Q16, the pilot site, in September 2013, both facing the same field of view (for more

Fig. 1. Photographs and original typical images of the phenocameras (PlantCam) monitoring sites at the Serra do Cipó, Brazil. (a) PlantCam system setup at the Reserva Vellozia field site; (b-c) fire passage and burned landscape of *campo rupestre*, respectively, occurred in the fire event of October 2014; (d-k) Images showing the burned vegetation right after the fire event on October 14th and the immediate post-fire vegetation regrowth between May 10th and May 20th 2015, respectively, at (d-e) Pedra do Elefante (PE) site; (f-g) Reserva Vellozia (RV) site; (h-i) Quadrante 16 (Q16) site; and (j-k) Cedro (CE) site.

details see **Table S1**). The other three sites (RV, CE, PE) have been monitored by the time-lapse PlantCam since October 2014, right after the extensive fire event that burned all four study sites (Fig. 1). We placed one camera per site facing the typical *campo rupestre* vegetation. The phenocameras at all sites were attached to a pole by the side of a local meteorological station. The timelapse PlantCam and Mobotix cameras were configured to capture one square JPEG image (2592 × 1944 pixels), and five landscape JPEG images (1280 × 960 pixels), respectively, in the first 10 min of each hour, starting at 6 am and ending at 6 pm (UC-3 Universal Time Coordinated).

2.3. Image processing and analysis

We visually screened the raw images to remove photographs where the vegetation view was obstructed (heavy rains, fog, dim light). The remaining images were analyzed as described by Alberton et al. (2014, 2019). Regions of interest (ROIs) were selected in the images of each site to capture the vegetation types of the *campo rupestre* (Fig. 2). We sampled ROIs for wet grasslands ($n = 5$), stony grasslands ($n = 4$), rocky outcrops ($n = 6$) and peatbog ($n = 1$), totaling 16 ROIs sampled for all the four cameras. We carried out field expeditions to identify and validate the vegetation types (Mattos et al., 2019) selected as ROIs in the field of view of each image site (Fig. 2).

All ROIs were analyzed regarding the relative brightness of red, green, and blue colour channels (RGB chromatic coordinates – RGBcc - Woebbecke et al., 1995). The normalized RGBcc index is considered the most suitable for detecting leafing transitions, and efficient for suppressing light variations (Alberton et al., 2014; Gillespie et al., 1987; Richardson et al., 2009; Sonnentag et al., 2012). We calculated the G_{cc} (green chromatic coordinate), a normalized vegetation index, related to the greening signal or vegetation leafing, and the most common camera-derived index applied in ecological studies (Alberton et al., 2014; Gillespie et al., 1987; Richardson et al., 2009; Woebbecke et al., 1995). The camera-derived vegetation index was calculated according to the equation:

$$\mathrm{Gcc} = \frac{\mathrm{G}}{(\mathrm{R} + \mathrm{G} + \mathrm{B})} \quad (1)$$

G_{cc} was calculated for each of the hourly images taken each day. In this study, we extracted one single value, taking the 50th percentile of all midday values observed daily (from 10 a.m. to 2 p.m.) to compose the G_{cc} time series of each ROI. This data filtering was the most suitable for

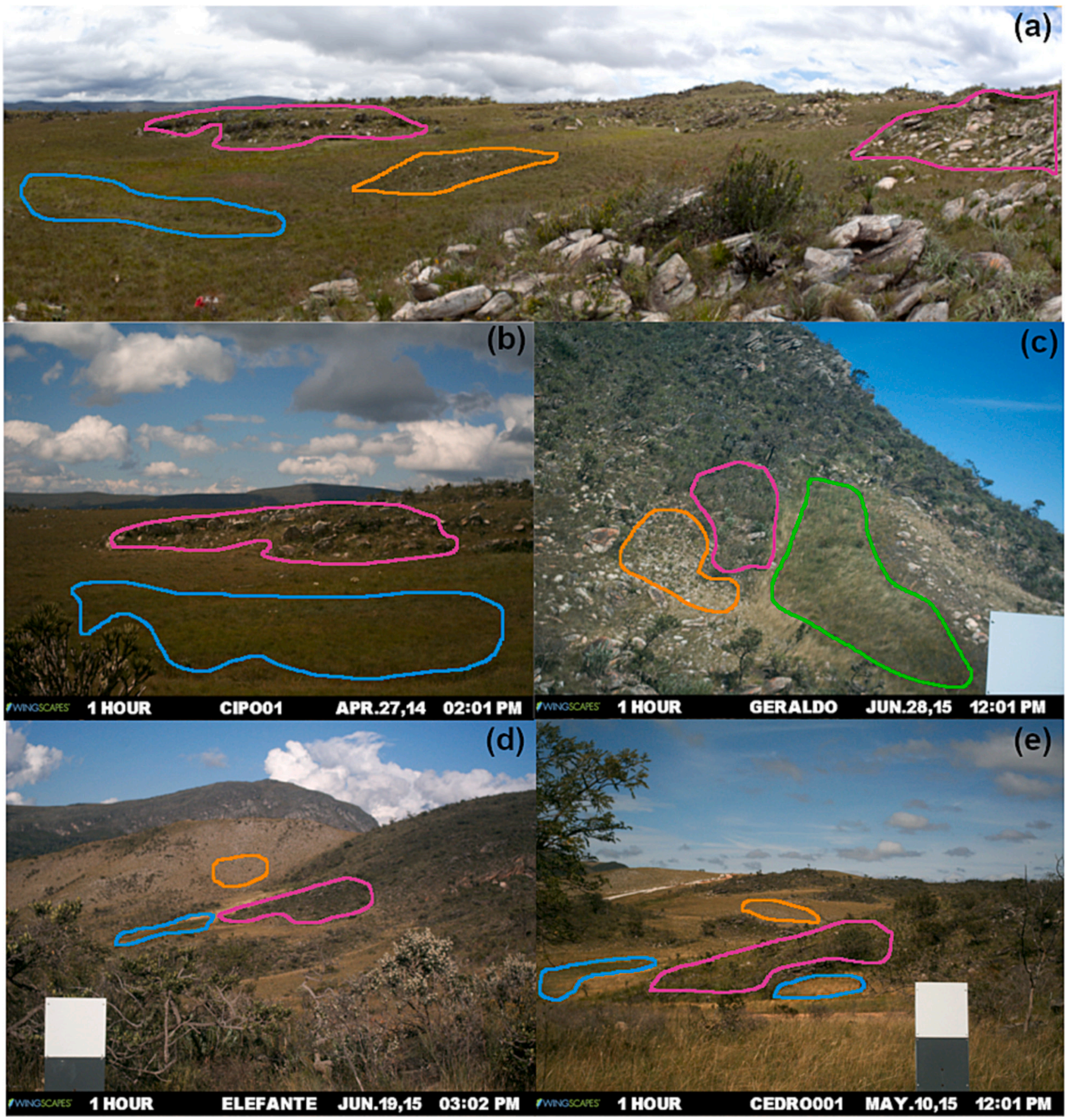

Fig. 2. Original images from the phenocameras monitoring the Serra do Cipó study sites, showing the selected regions of interest (ROIS): (a) Q16 (Mobotix camera), (b) Q16 (PlantCam), (c) Reserva Vellozia (PlantCam), (d) Pedra do Elefante (PlantCam), and (e) Cedro (PlantCam). Colored lines represent ROIS of each vegetation type: rocky outcrop (pink line), stony grassland (orange line), wet grassland (blue line), and peatbog (green line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

our dataset since cameras are placed in different cardinal positions along sites due to setup limitations. To minimize noise in the time series information (G_{cc}) due to illumination changes, weather, season, and time of the day, we aggregated daily values in a 3-day window (adapted from Sonnentag et al., 2012), smoothing G_{cc} time series without losing important phenological transitions (Alberton et al., 2019, 2023).

2.4. Data analysis

2.4.1. Assessing immediate post-fire vegetation regrowth

We fitted Generalized Additive Mixed Models (GAMM) to the G_{cc} time series, using the time (sequence of observations) as a smooth independent variable (Alberton et al., 2019). Afterward, we generated 10,000 independent simulations of the fitted curve to calculate the derivative of each simulated curve at each time step, building a confidence interval for the rate of changes (with a derivative significantly different from zero) (Fig. 3). From the derivatives, we were able to calculate a green-up rate, corresponding to the significant period of increase in greenness values reaching the peak of the rising curve (Fig. 3), using observation from the first day after the fire, up to the complete vegetation coverage (50 observations from a three-day time series, equivalent to 150 days). We applied the derivative approach to extract the green-up rate from the G_{cc} time series of all ROIs. Since the green-up metric is based on a linear regression of increasing values of G_{cc} in the function of time, we used the slope value of the model to be compared as a potential regrowth rate among the vegetation types.

2.4.2. Short-term vegetation recovery

We calculated phenological metrics to evaluate the significant periods of increasing and decreasing greenness along the year, defined as the Start of the growing season (SOS)— a day of year representing the beginning of the growing season and measured as the 20% of a significant derivative from the total seasonal amplitude on the left side of the curve; End of the growing season (EOS)—a day of year representing the end of the growing season and measured as the 80% of a significant derivative from the total seasonal amplitude on the right side of the curve; and of Growing season length (GSL)—representing the duration (days) of the growing season and calculated as the difference between SOS and EOS (Alberton et al., 2019). Then, to evaluate the short-term post-fire vegetation recovery among all ROIs, we extracted the phenological metrics of SOS, EOS, and GSL from the following growing seasons (GS): *Pre-fire* = GS in the year before fire (2013–2014, when available); Fire = the GS just after the fire (2014–2015); *Post-fire 1* = the GS of the subsequent year (2015–2016); *Post-fire 2* = the third GS after fire (2016-2017); and *Post-fire 3* = the fourth GS after fire (2017-2018).

3. Results

The visual detection of the fire occurrence was clear among all four sites monitored that encompassed the most common vegetation types of the quartzitic *campo rupestre*. The fire event was also screened in the time-lapse digital images (Fig. 1) and by the G_{cc} time series (**Fig. S3**), detecting the increasing growth dynamics for all vegetation ROIs (Fig. 4). The phenocameras tracked as well, the differences in the post-fire G_{cc} patterns among vegetation types (Fig. 4).

According to the post-fire G_{cc} curves, the wet grasslands and peatbogs ROIs presented a faster and marked post-fire increase in the G_{cc} values (Fig. 4a and g), reflected in the slope values of post-fire green-up rates (**Table S2 and** Fig. 4b and h). We assessed the peak date of the G_{cc} curve, representing the complete post-fire vegetation coverage that occurred for each habitat's ROI analyzed. For wet grasslands, the peak dates of G_{cc} curve were between November 3rd and November 21st, or day of the year (DOY) 307 and 325, respectively, and on November 30th (DOY = 334) for the peatbog, both less than two months after the fire event. In contrast, the stony grassland and rocky outcrop vegetation types presented a smoother and slower pattern of post-fire G_{cc} increase (Fig. 4 **c and e**) with lower values of green-up rates (**Table S2 and** Fig. 4 **d and f**). The peak of post-fire vegetation coverage occurred between November 9th and March 12th (DOY = 313 and 71) for the rocky outcrop, and between December 3^{rt} and March 12th (DOY = 337 and 71) for the stony grassland, up to five months after the fire event.

By expanding the post-fire time series analysis to the previous and the subsequent growing seasons (GS), we detected differences in the leafing transition dates of G_{cc} times series among cycles (**Table S3** and Fig. 5). Considering the average of all ROIs of the *campo rupestre*, at the *Pre-fire* GS, the SOS mean dates started at DOY 310 ± 34.5, and EOS occurred at DOY 224 ± 25.5 in the following year, resulting in a growing season length (GSL) of 279 days ±27.7 (Fig. 5). For the *Fire* GS, SOS occurred around DOY 303 ± 24.7, while EOS had an earlier occurrence at DOY 188 ± 96.1 in the following year, which resulted in the shortest GSL observed (208 ± 85.2) (Fig. 5). The *Post-fire 1* GS presented the earliest SOS (DOY 282 ± 23) and EOS (DOY 173 ± 33.3) mean dates, resulting in a GSL of 255 days ±19.9. *Post-fire 2* and *Post-fire 3* growing seasons presented increasing GSL values, with 296 ± 20.6 and 264 ± 1.4, respectively (Fig. 5c).

Leafing transition dates varied among vegetation types as well (**Table S3**). In general, the GSL mean values of each vegetation type followed a similar pattern of variation across the years, but with different ranges of variation among them (Fig. 6). Wet grasslands and the peatbog presented the higher range of variation of leafing transition dates among the years, reaching the smallest mean values of GSL (248 days ±51.1 and 246 days ±66.8, respectively) (Fig. 6 **a and d**). Conversely, rocky outcrops and stony grasslands times series presented the lowest range of variation of leafing transition dates among all years and the highest mean values of GSL (268 ± 18.5 and 265 ± 33, respectively) (Fig. 6 **b and d**).

4. Discussion

The near-surface monitoring system allowed us to detect fire and

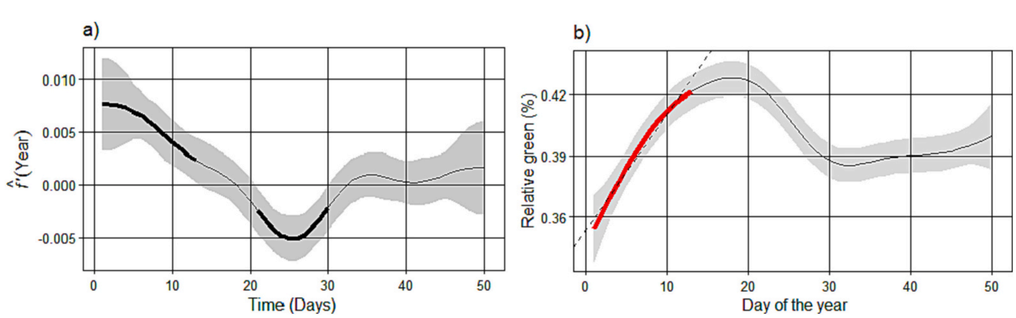

Fig. 3. Graphical example showing the derivative calculation approach for the calculation of the vegetation regrowth rate. (A) fitted GAM model with identified derivatives over the phenological time series, (B) fitted linear models over the increasing side of the curve (dashed line) and estimated green up (red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

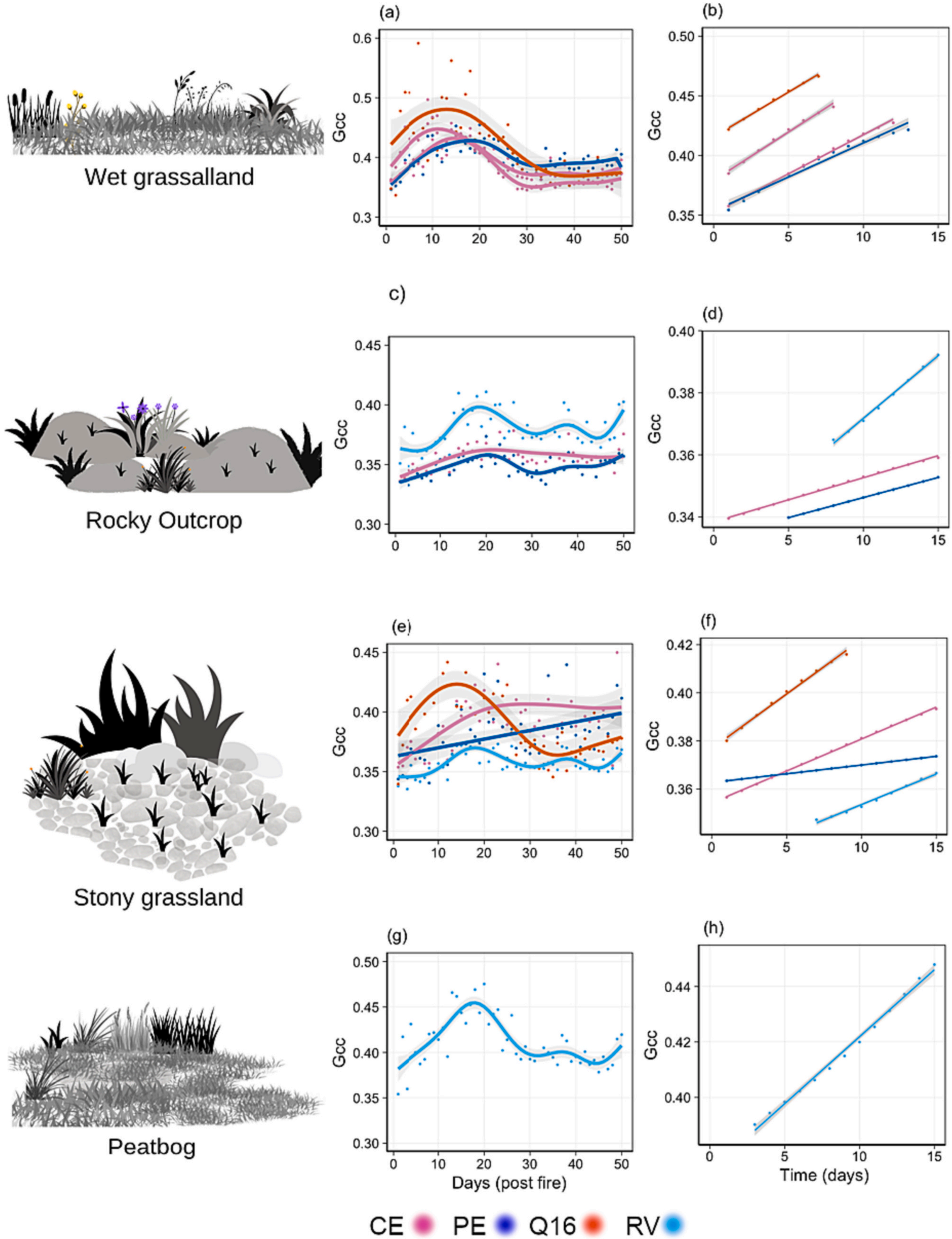

Fig. 4. Immediate post-fire vegetation regrowth (three-day G_{cc} time series) and green-up rates (linear model estimate of increasing G_{cc} values after the fire) for each *campo rupestre* vegetation type monitored by phenocameras at Serra do Cipó, Brazil. Vegetation regrowth (left side), lines represent the fitted GAMM models with their confidence intervals (gray shaded areas), dots represent observed data; Green up rate (right side). G_{cc} time series were extracted from the ROIs of each vegetation type: (a-b) wet grassland; (c-d) rocky outcrop; (e-f) stony grassland; (g-h) peatbog. Colors refer to study sites: CE (1101 masl); PE (1255 masl); Q16 (1303 masl); RV (1150 masl). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

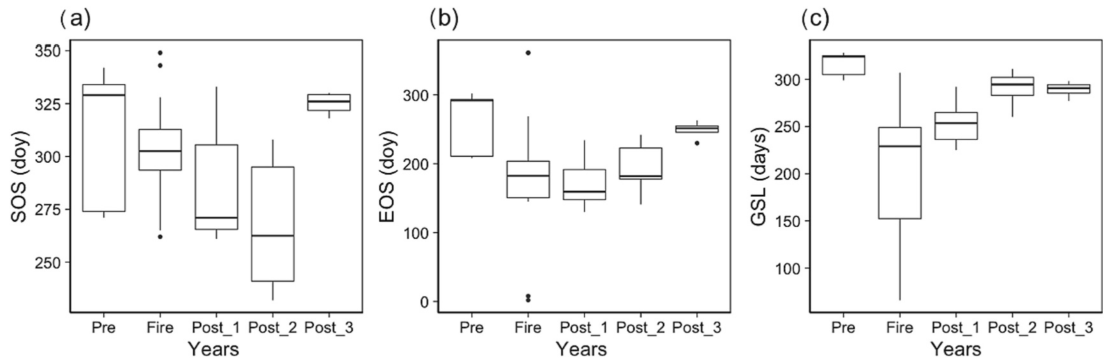

Fig. 5. Boxplots of the phenological metrics extracted from the three-day G_{cc} time series during the growing seasons of *Pre-fire*, *Fire*, *Post-fire 1*, *Post-fire 2*, and *Post-fire 3* from all the ROIs of the *campo rupestre* study sites at Serra do Cipó, Brazil. (a) Start of growing season (SOS), (b) End of growing season (EOS), and (c) Growing season length (GSL).

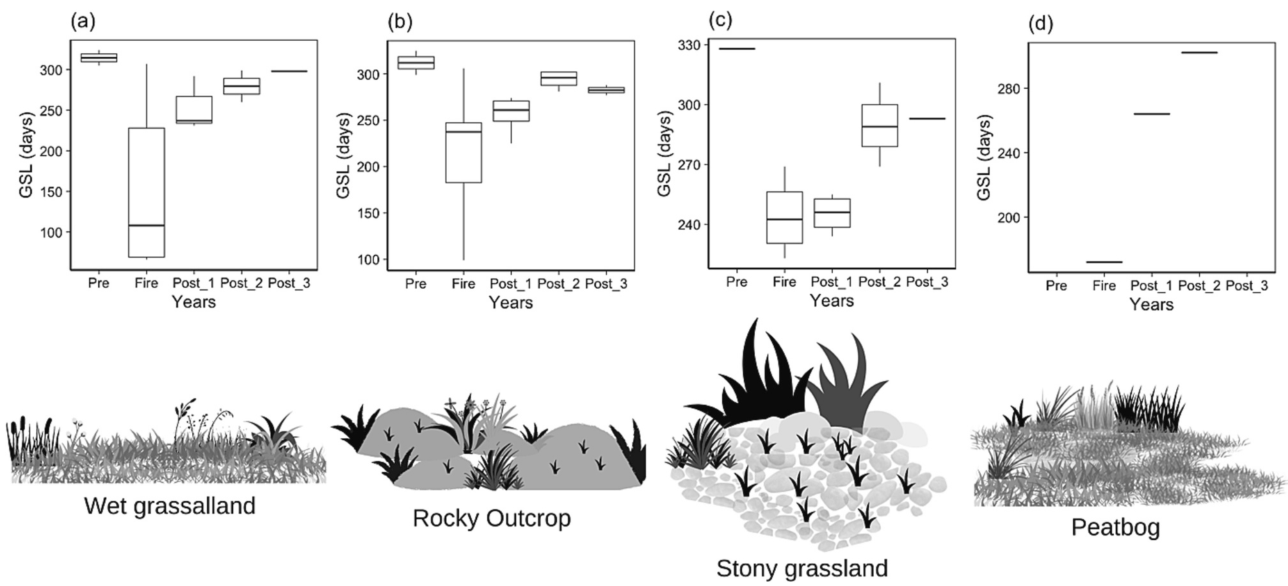

Fig. 6. Boxplots of the mean values of the growing season length (GSL) extracted from the three-day G_{cc} time series during the following growing seasons: *Pre-fire*, *Fire*, *Post-fire 1*, *Post-fire 2*, *Post-fire 3*, for each one of the *campo rupestre* vegetation types: (a) wet grasslands, (b) rocky outcrops, (c) stony grasslands, and (d) peatbog.

evaluate the immediate regrowth and post-fire vegetation recovery across the four major vegetation types of the *campo rupestre* at a fine temporal scale. Camera-derived observations tracked differences among each vegetation type regarding speed and pattern of vegetation recovery, revealed by their post-fire green-up curve rates. In general, moist environments, such as the wet grassland and peatbog, achieved the highest and faster rates of post-fire green-up, while in the driest stony grassland and rocky outcrop, recovery was slower, despite the reported high resilience after a fire (e.g., Figueira et al., 2016; Le Stradic et al., 2018b).

The phenological metrics indicated fire as one of the major forces driving changes in leafing dynamics by shortening the length of the post-fire growing seasons. We estimated a fully recovered growing season length to occur in the third year after the 2014 fire. The fast recovery of *campo rupestre* grass-dominated vegetation is likely the result of the regeneration strategies of the plant community, mainly the resprouting from underground organs of the perennial herbaceous layer (e.g.: Simon et al., 2009; Le Stradic et al., 2018a, 2018b; Pilon et al., 2019, 2021; Zupo et al., 2021). However, the observed differences in the phenological recovery among vegetation types indicated that soil humidity defines the fast recovery of peatbog and wet grassland. However, differences in community structure and composition (Mattos et al., 2019) may also affect fire recovery (Le Stradic et al., 2018b). For instance, the number of species and individuals may increase and stabilize six to eight months after a fire in grass-dominated savannas in Southeastern Brazil. At the same time, the percentage of bare soil decreases until reaching the pre-fire values (Pilon et al., 2021).

Phenocamera monitoring proved essential to assess the dynamic vegetation response across the *campo rupestre*. The camera-derived time series detected the fast start of vegetation regrowth a single day after the fire event for some ROIs, indicating an accelerated post-fire vegetation recovery. A greening peak was reached within the first four months after the fire event, demonstrating the quick after-fire recovery pattern of the *campo rupestre* ecosystem. Our results concur with on-the-ground local observations (Kolbek and Alves, 2023; Neves and Conceição, 2010; Le Stradic et al., 2018b; Carvalho Barbosa et al., 2014) reporting fast species responses (especially flowering) within a few months after the fire. The dominance of perennial grasses (Le Stradic et al., 2018a), the existence of the resprouters (Neves and Conceição, 2010; Pilon et al., 2021; Zupo et al., 2021), species able to resprout from any plant structure (Bell, 2001; Keeley and Fotheringham, 2000), and the inherent characteristics of each vegetation type (Le Stradic et al., 2015; Le Stradic et al., 2018b, Mattos et al., 2019, Loiola et al., 2023), appear to drive the fast and dynamic fire response detected for *campo rupestre* vegetation mosaic.

A remote sensing study of the fire dynamics across the South

Espinhaço range, including all the Serra do Cipó region, suggests a moisture-dependent fire regime, mostly defined by the drought during the ignition season, and a high recovery potential of *campo rupestre* landscape, under the prevalence of low and moderate fire frequencies (Alvarado et al., 2017). Moreover, the fire event evaluated here occurred in the middle of October, in the transition between the dry to the rainy season, which could favor the fast recovery of vegetation (Alvarado et al., 2017). Short-term postfire spectral dynamics studies have shown a faster recovery of grasslands burned in the middle of the dry season than grasslands burned in the early dry season, suggesting the effects of rain on vegetation recovery (Alves et al., 2022). A recent study has also reported a fast post-fire recovery of *campo rupestre* vegetation, reporting no differences between the time of return to a pre-fire state in burned grasslands at the beginning of the rainy season compared to the control unburned plots (Araújo and Conceição, 2021).

Our phenological metrics analysis demonstrated that fire may drive changes in the *campo rupestre* growing seasons after the vegetation is burnt. The fire impacted leafing patterns by shifting leaf flushing and senescence onsets, as observed by the shortened GSL values just after the fire and in the first post-fire growing season. Leaf phenology plays a key role in ecosystem productivity, by controlling photosynthetic rates and carbon cycle (Reich, 1995; Richardson et al., 2013; Piao et al., 2019). Camera-derived G_{cc} index is widely used to track phenological leafing transitions and has been related to gross primary productivity in temperate forests, and grasslands (Peichl et al., 2015; Toomey et al., 2015), and more recently to tropical ecosystems (Alberton et al., 2023).

Leafing dynamics in *campo rupestre* were fast and the different grassy vegetation types, located very close to each other in the landscape, presented varied responses after a fire. The complex landscape mosaic, determined by the different vegetation types, the irregular topography, and various soil substrates, are likely driving the fire regime to cause distinct effects on vegetation (Anjos et al., 2022). Phenocameras were applied as a new source of data to provide fine-resolution analysis of post-fire events across species-rich and heterogenous grassy landscapes. A similar post-fire monitoring analysis using the current satellite products would not be suitable for tracking the vegetation's fast response given the lack of imagery resolution at the scale of each vegetation type (Streher et al., 2017, Medeiros et al., 2023). For instance, MODIS time series have lower spatial accuracy, considering that a single 250-m pixel would include a mix of different vegetation types (e.g., wet grasslands, rocky outcrops, stone grasslands, and peat bogs), besides the low temporal frequency.

Concerning fire detection, it is important to highlight that camera systems intended to monitor wildfires may have some practical limitations in terms of the total area of coverage that cameras can reach, the uncertainty of capturing the fire occurrence from a fixed camera position, or the fact that fire can damage the camera itself. Implementing a camera network with sensors spread along target sites with a wide field of view could address those shortcomings. Furthermore, strategies, such as installing cameras right after the fire event, and extending phenocamera application into field experiments to monitor burned and unburned plots, could leverage the reliability of cameras as post-fire monitoring systems.

5. Conclusions

Time-lapse cameras are an accessible tool to monitor, predict effects, and follow the regrowth process of vegetation after fire. The camera-derived greening index contributes to filling the gap between on-the-ground and satellite land-surface phenology, with future scale-up of fine-scale temporal data (e.g.: Khare et al., 2022) allowing large-scale tracking of fast-response tropical ecosystems. The accessible, low-cost, and easy setup phenocameras may improve the amount of precise, on-site, fine-scale information on fire response and recovery, not yet available for reserves and national parks, with a positive impact on their conservation, restoration, and future management policies (Fernandes et al., 2018, 2020). In this sense, phenocamera monitoring can foster studies assessing changes in fire effects over long post-fire times (Giorgis et al., 2021). Fine-scale leaf phenology analysis is an accurate indicator of plant responses to wildfires and may help evaluate fire impact on ecosystem dynamics and serve as an indicator of the resilience of natural grasslands (Buisson et al., 2017), particularly in tropical grassy ecosystems with a fast postfire recovery. Phenocameras monitoring can also contribute to restoration projects with the application of phenological metrics as an indicator of the restoration process (Alvarado et al., 2017; Buisson et al., 2017). Establishing a long-term record of the vegetation regrowth will provide insights into how tropical grasslands are responding to environmental changes and especially climate change, a sensitive factor for mountain ecosystems.

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Author's contributions

BA, LPCM, and RT designed the research; BA and LPCM set up the experiment and collected the data; BA and RT analyzed the data, and all authors interpreted the outputs; BA wrote the initial version of the manuscript, and all authors contributed to its revision and gave final approval for publication.

Declaration of Competing Interest

The authors declare that they have no competing interests.

Data availability

The dataset supporting the conclusions of this article is available in the Figshare repository, at https://figshare.com/s/92a8fa1015fd07fe25b7.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoinf.2023.102341.

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