Title page

i. Title

Monitoring the seasonal functioning of tropical ecosystems with phenocams

ii. Full name of the authors

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iv. Abstract and keywords

Abstract: Phenology is an essential biodiversity variable, but land surface phenology is challenging in cloudy tropical regions while field observations are time-consuming and sparce in time. Phenocams offer opportunities that have been barely explored in Africa. Here, we present the first results of a phenocam network installed in Gabon. The two years of images show the seasonal and bimodal functioning of forest canopy, mimicking rainfall seasonality, and the unimodal functioning of savanna, associated with the long dry season and fire. This work is encouraging though the challenge is to maintain phenocams over the long-term and automate the signal analysis.

Keywords: Deciduousness, Dry season, Greenness, Phenology

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v. Main text

1. Introduction

A myriad of growth and life strategies have been identified in the tropics (Abernethy, Bush, Forget, Mendoza, & Morellato, 2018; Sakai, 2001) encompassing irregular and regular phenologies, and among them, sub-annual, annual, supra-annual and continuous patterns (Newstrom, Frankie, & Baker, 1994). Annual cycles were found to dominate in a cross-site analysis of flowering across tropical Africa (Adamescu et al., 2018) and in specific sites, Lopé National Park (NP) in Gabon (Bush et al., 2017) and Luki Biosphere Reserve (BR) in the Democratic Republic of the Congo (Angoboy Ilondea et al., 2019). Central African tropical forest canopies also show a high proportion of fully deciduous trees and a strong seasonal functioning (Gond et al., 2013; Philippon et al., 2019). The important deciduousness of tropical forests in central Africa is probably due to their drier climates in comparison with the other tropical regions (Guan et al., 2015).

Vegetative phenology has been historically less studied than reproductive phenology in central Africa because earlier studies were related to animal diet and focused on fruiting (Brugiere, Gautier, Moungazi, & Gautier-Hion, 2002; Tutin, Williamson, Rogers, & Fernandez, 1991; White, 1994). Also, since field observations are extremely time-consuming, phenology surveys target a few individuals monitored at a low temporal resolution (usually once a month) not suitable to capture quick changes in leaf phenology (Bush et al., 2018). Leaf renewal can be extremely rapid with one week between leaf shedding and unfolding for *Prioria balsamifera* in Luki BR (Angoboy Ilondea et al., 2021), a relatively dry site (c. 1,200 mm yr^{-1} rainfall) at the southern tip of the moist forest biome (Aleman et al., 2020). In addition, the dense cloud cover that allows persistence of forests under dry and seasonal climates in central Africa (Philippon et al., 2019) also prevents analyses using satellite observations (Adole, Dash, & Atkinson, 2018). Other approaches are thus required to monitor canopy seasonality which is of great importance to unravel ecosystem functioning and responses to seasonal drought. Near-surface remote sensing, *i.e.*, images automatically collected at high temporal frequency from fixed-point by digital cameras, started almost two decades ago (Richardson et al., 2007) and allowed to investigate the seasonality of trees and forest ecosystems worldwide (Brown et al., 2016). In the tropics, the coverage is still limited, but there is a huge potential for the expansion of networks that already encompass a variety of vegetation types such as the cerrado (Alberton et al., 2014) and other seasonally dry tropical communities (Alberton et al., 2019) of Brazil, and tropical forests as done in the central Amazon (Lopes et al., 2016) and in Borneo (Nagai et al., 2016). The phenological monitoring of African trees is probably different from trees in other forested ecosystems, both tropical and temperate, because of the high seasonal functioning (Gond et al., 2013), and the coexistence of evergreen and semi-deciduous species in the canopy (Gorel et al., 2025). Yet, only few studies in central Africa investigated leaf phenology, but see Angoboy Ilondea et al., (2021) in Luki, and Kearsley et al., (2024) in Yangambi.

In this study, our aim is to show the potential of using phenocams to monitor the seasonal functioning of tropical trees and ecosystems in central Africa. We present a methodological approach developed for the processing of phenocam images taken in the forest-savanna mosaic landscape found at the northern and eastern limits of Lopé NP and where the ecotone forms a distinct tree community

(Cardoso et al., 2021). The site is located near the Equator (Figure 1) and shows a bimodal distribution of monthly rainfall (Bush, Jeffery, et al., 2020). We tested this approach by addressing the following research questions. 1) To what extent canopy greenness shows a seasonal trend that is related to climate seasonality? 2) Do forests and savannas show similar trends in greenness seasonality? Indeed, distinct leaf phenology strategies have been demonstrated for forest and savannas and interpretated as a temporal niche separation (Higgins, Delgado-Cartay, February, & Combrink, 2011).

2. Material and methods

2.1 Phenocam images

A total of 12 Moultrie Wingscapes TimelapseCam Pro were installed on trees between September 2019 and November 2021 near the “Station d’Etudes des Gorilles et des Chimpanzés” (SEGC, Figure 1). For the camera deployment in the field, we used the topography to maximise the view on forest patches given the device used and which has lens field of view of 40°. The phenocams were mounted on trees or poles at 1-2 m height, and were parametrized to collect two JPEG images (6080 × 3420 pixels, ~ 3 Mo) each day at 11 and 12 am to limit the influence of the sun angle (Alberton et al., 2017). We recognize that more images would have been better, but we first let the phenocams running during one year without any maintenance. Eight AA lithium batteries per camera powered image acquisition for one year. After the first year when cameras were rarely checked and suffered changes in the field of view, we changed the protocol to check phenocams every three months. In this study, we focused on the three phenocams with the longest time series, phenocams 005, 006 and 007, which collected 1,465, 1,181 and 1,459 images, respectively, from the 24th of September 2019 to the 22th of September 2021. The number of images differs due to technical problems related to wind or maintenance.

2.2 Rainfall and temperature

Weather data were acquired onsite during the period covered by the phenocam images at the SEGC (11.605 E, -0.201 N) and the weather station is located in a savanna environment (Bush, Jeffery, et al., 2020). A manual rain gauge recorded total daily rainfall at 8 am each morning. Daily temperature was recorded automatically using a TinyTag Plus 2 data logger (Gemini Data Loggers https://www.geminidataloggers.com/data-loggers/tinytag-plus-2, some of which record both temperature and relative humidity). The timeseries is however incomplete for temperature with five missing months in 2021. Onsite daily rainfall data showed annual rainfall of 1,555 mm, 1,365 mm, and 1,765 mm, respectively for 2019, 2020, 2021, in line with the trends observed between 1984 and 2018, with a mean annual rainfall of 1,500 mm (Bush, Jeffery, et al., 2020) and biannual cycles with two rainy (March-April-May and October-November) and dry (June-July-August-September and December-January-February) seasons (Figure 1b). The short dry season is known to be less dry and more variable than the long dry season which is very consistent (Bush, Jeffery, et al., 2020) and light-deficient (Philippon et al., 2019).

2.3 Images processing

We developed a framework for processing the phenocam images and the first step consists of selecting a reference image that fixes the field of view (step 1, Figure 2). Regions Of Interest (ROIs), such as the extent of the forest and savanna, are then manually drawn in QGIS by visual interpretation of the reference image. Since the angle of view fluctuated, the reference image was used to align all other images (step 2). This was carried out via a python code developed previously (Dandrifosse, Carlier, Dumont, & Mercatoris, 2021) and combining the A-KAZE and ECC methods implemented in the OpenCV-Python library (version 4.1.0.25 and Python 3.7). The feature-based A-KAZE algorithm was first used to roughly align images with the reference image, as required for the ECC method. A-KAZE is based on key points selected for their invariance to change in brightness, contrast, scale, or rotation, which are employed as corresponding points during the alignment process between the input image and the reference image. Then, the ECC algorithm estimates the geometric transformation (warp) between the input and the reference image and returns a warped input image close to the reference image. After alignment, poor-quality images due to heavy rainfall, dense clouds, and/or faulty alignments were removed manually (step 3) and areas not common to the reference image (black edge stripes) were removed in R (step 4), which was also used for subsequent steps.

We then calculated the Green Chromatic Coordinate (GCC) for each pixel in each image (step 5).

$$GCC = G / (R + G + B) \quad (1)$$

where G, R and B are the red, green and blue digital numbers corresponding to the intensity of each primary colour. The GCC is the most widely used ‘chromatic coordinates' index for extracting phenological information from RGB channels (Gillespie et al., 1987), being effective for extracting leaf colour changes and getting rid of light variation (Sonnentag et al., 2012) including in tropical regions (Alberton et al., 2014, 2019; Lopes et al., 2016). Afterwards, the GCC values were averaged for each ROI in each image (step 6).

2.4 Data analyses

To reduce the noise in the GCC data and to detect seasonal trends in GCC time series, we explored several smoothing approaches such as moving average. Here, we show the results of fitted Generalized Additive Mixed Models (GAMMs) that were used previously in phenology analyses based on field observations (Polansky & Robbins, 2013) and on GCC timeseries from phenocam images (Alberton et al., 2019). This was done separately for the forest and savanna ROIs using the restricted maximum likelihood smoothing method and setting the number of basic functions to 15. The GCC timeseries were related to climate seasonality, and specifically to monthly rainfall and average temperature. The two variables were combined for the whole period in the style of a Walter-Lieth climate diagram. In such diagram a dry month corresponds to monthly rainfall below twice the average temperature (approx. 50 mm and 25°C, respectively) and a very wet month corresponds to more than 100 mm rainfall. All analyses were done in R using the following packages: *raster* for image processing (Hijmans, 2017), *lubridate* for dealing with dates (Spinu et al., 2024), *dplyr* for data management (Wickham et al., 2023), *mgcv* for fitting GAMM models (Wood, 2025), and *climatol* for the climatic diagram (Guijarro, 2025).

3. Results

We first explored the seasonality of canopy greenness and local climate. Variation in GCC for the forest ROI was bimodal for phenocams 006 and 007 (Figure 3b and c) and the peaks occurred during the rainy seasons (in blue) and troughs during the dry seasons (in red, on the climatic diagram reported for the whole study period, Figure 3d). The larger trough occurred at the end of the long dry season which lasts from June to September. This bimodal trend in forest greenness was less clear for the phenocam 005 probably because the peak in greenness was earlier than the start of monitoring (Figure 3a). Also, the data recorded by this phenocam were noisier with large daily and weekly variations (Figure 3a), perhaps because of camera calibration. The GCC varied between 0.28 and 0.41 for this specific phenocam, while the GCC variation was much more restricted, between 0.32 and 0.36, for phenocams 006 and 007.

We then explored whether the savannas show the same trend in greenness seasonality as the forest patches. For the savanna ROIs, the GCC shows a broad peak from October to November which corresponds to the rainy season, and this peak can last until December, January and February, the short dry season (Figure 3b, c and d), during which the GCC starts decreasing to a minimum value observed at the end of the long dry season, when savanna fires are initiated onsite. Savanna fires were recorded for the phenocams 006 (no fire in 2020, burnt on the 27th of August 2021, Figure 3b) and 007 (burnt on the 8th of September 2020 and on the 28th of August 2021, Figure 3c). Shortly after burning, savanna GCC values sharply increased and followed the same cycle. For the same phenocam, the range of GCC values was larger for the savanna than for the forest ROI (Figure 3).

4. Discussion

The two years of images taken by three phenocams in Lopé NP provided encouraging results confirming the potential of this technology to monitor the seasonal functioning of tropical ecosystems in central Africa. In addition, these results highlight the diversity of patterns found in the forest-savanna mosaic landscape since our phenocams recorded both the biannual forest green-up cycle, aligned with monthly rainfall distribution, and the annual savanna green-up cycle, aligned with the long dry season and the savanna burning (Jeffery et al., 2014). The amount of data from the three timeseries analyzed so far and including a complete year and a second one with missing data, is comparable to the few published studies in tropical forests, based on a single phenocam mounted on a tower and running over one year in the central Amazon (Lopes et al., 2016) and over two years in Borneo (Nagai et al., 2016).

In contrast to satellite observations that are made over wide areas, but at low spatial and temporal resolutions, near-surface remote sensing offers observations at the scale of tree crowns and at a high temporal resolution as earlier developed globally (Brown et al., 2016) and for the tropics (Alberton et al., 2017). Here, we demonstrated that it is possible to use devices that are cheap and easy to set up, and with a minimum parametrisation of only two images a day, we found a bimodal signal in forest greenness, a trend that was previously detected with the Enhanced Vegetation Index of MODIS satellite further inland (Gond et al., 2013) and across the region (Philippon et al., 2019). With two greenness peaks during the rainy seasons, canopy functioning appeared relatively seasonal for an evergreen forest belonging to the “Atlantic inland evergreen domain” of Réjou-Méchain et al. (2021),

probably because the canopy still holds deciduous species (Bush, Mitchard, et al., 2020). Greenness is minimum during the long dry season and only a slowdown is observed during the short rainy season, when both fruit quantity and diversity peak onsite (White, 1994). In Lambir NP in Malaysia where rainfall is greater (2,600 mm yr^{-1}), no seasonal trend was detected at the whole canopy level (Nagai et al., 2016) but leaf colouring and flowering were observed at the crown level. In the central Amazon, highly seasonal with a sunny dry season, rapid large-amplitude negative/positive changes in GCC for individual tree crowns were interpreted as leaf loss/flush events (Lopes et al., 2016). The diversity of leaf phenology strategies remains to be explored, and requires a tree crown approach.

Here, we developed a framework for the processing of phenocam images. The alignment approach we employed, combining the A-KAZE and ECC algorithms, introduces a novel and straightforward method for generating timeseries within regions of interest (ROIs). This method earlier developed by Dandrifosse et al., (2021) effectively addresses perspective shifts, which can frequently occur due to maintenance routines, data downloads, or environmental conditions. However, although these algorithms effectively handle minor deviations in viewing angles, substantial shifts in the camera's perspective can, on occasion, lead to significant pixel loss. Consequently, we strongly recommend securely fastening camera mounts to guarantee a consistently stable field of vision over time. For the deployment of new phenocams, it is essential to use a stable support (metal stake, telephone pole) and fixation ties that are resistant to temperature and humidity variations. Similarly, ensuring that growing vegetation does not obstruct the field of view is vital. Regular maintenance (every three months onsite) should include clearing vegetation from the phenocam's field of view and minimizing phenocam manipulation to prevent movements and misalignment with the reference scene. It is also important to protect the phenocam against lightning which is frequent in the tropics and in central Africa (Albrecht, Goodman, Buechler, Blakeslee, & Christian, 2016). Two of our phenocams were indeed destroyed by lightning in December 2021. We developed our approach with open-source tools (QGIS, python, and R) but for user convenience, we intend to develop the analysis pipeline into a single program (and language), likely python or R, the latter already includes several packages dedicated to the analyses of phenocam images. We also intend to develop an interface to aid phenophase photointerpretation for individual tree crowns, with the potential to undertake species level observation for dominant canopy species. This would facilitate calibration datasets for algorithm development. In comparison with other devices, the cameras we used are relatively cheap (125€), easy to parametrize and to set up, and can be implemented for phenology monitoring in extremely remote areas, since camera and image file format have been shown to be of secondary influence (Sonnentag et al., 2012). To better filter the signal, it would be desirable to increase the number of pictures per day. Taking into account the data storage capacity of Wingscapes TimelapseCam Pro, a shooting time spanning 10 to 14 hours (Alberton et al., 2014), along with quarterly battery replacement and data archiving practices, we estimate that the image capture rate could reach as high as one image every three minutes with a maximum SD card of 32 Go (imposed by the phenocam model) and an average image size of 3.3 Mo (4 hours of image capture, 20 images per hour over 90 days leads to 23.2 Go). Finally, the data gaps in the time series analysed are unfortunate, but increasing the frequency of maintenance is difficult. Solutions for real-time data transfer needs to be explored, but are not yet feasible in many places of central Africa.

To conclude, the approach outlined in this study, along with the cost-effectiveness and suitability of phenocams for remote deployment, establishes them as a highly promising tool for researchers committed to investigating environmental changes in tropical forests and savannas across Africa and the global tropics, where advance and apply phenological research is urgently needed (Sullivan et al., 2023).

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vii. Data Availability Statement

The raw data (images and time series) and R codes will be made available upon request.

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ix. Tables (each table complete with title and footnotes)

x. Figures

Figure 1. Phenocams installed in Lopé NP, Gabon. The location of the “Station d’Etudes des Gorilles et des Chimpanzés” (SEGC) is shown in Gabon (a) and the Walter–Lieth diagram showing rainfall (in blue) and temperature (in red) is provided (b). The phenocams installed in the field are also located with their respective reference image (c).

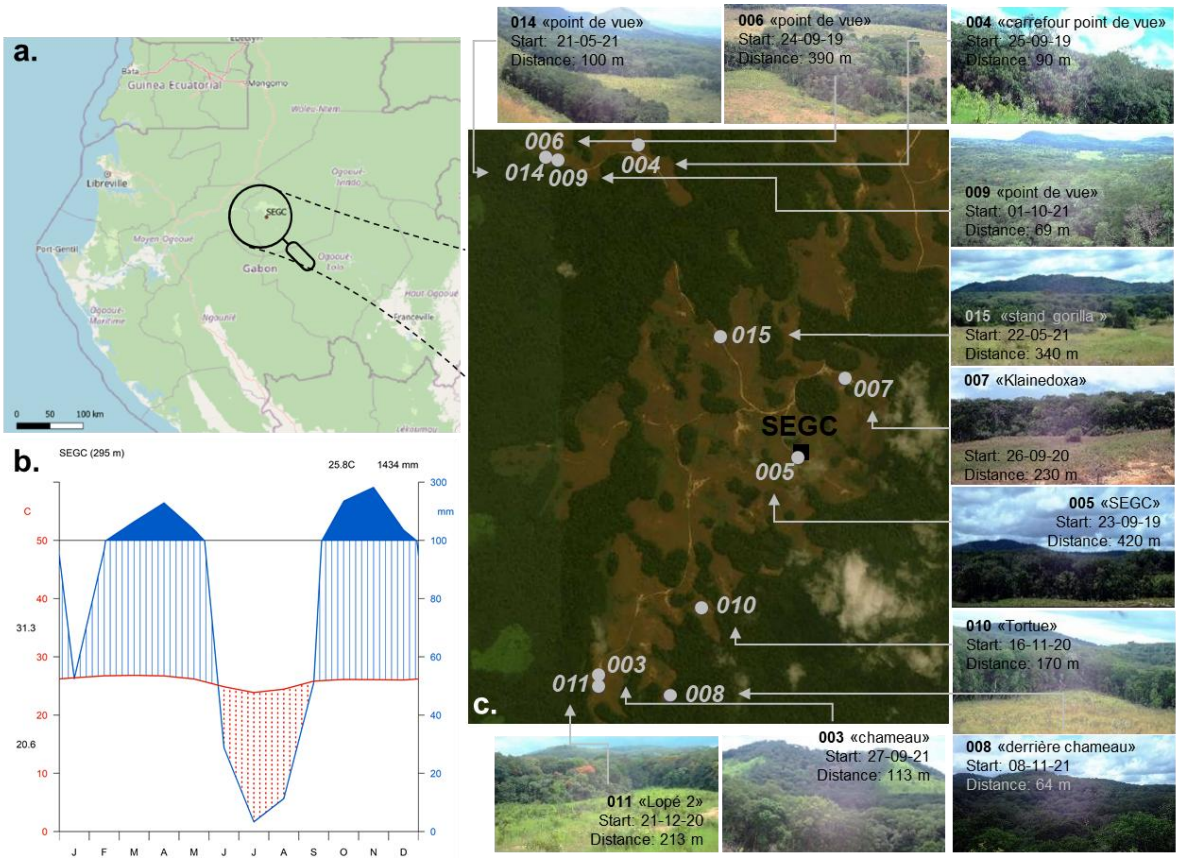

Figure 2. Analytical framework developed for the processing of phenocam images. The software used, either QGIS, Python or R is indicated with the respective logo.

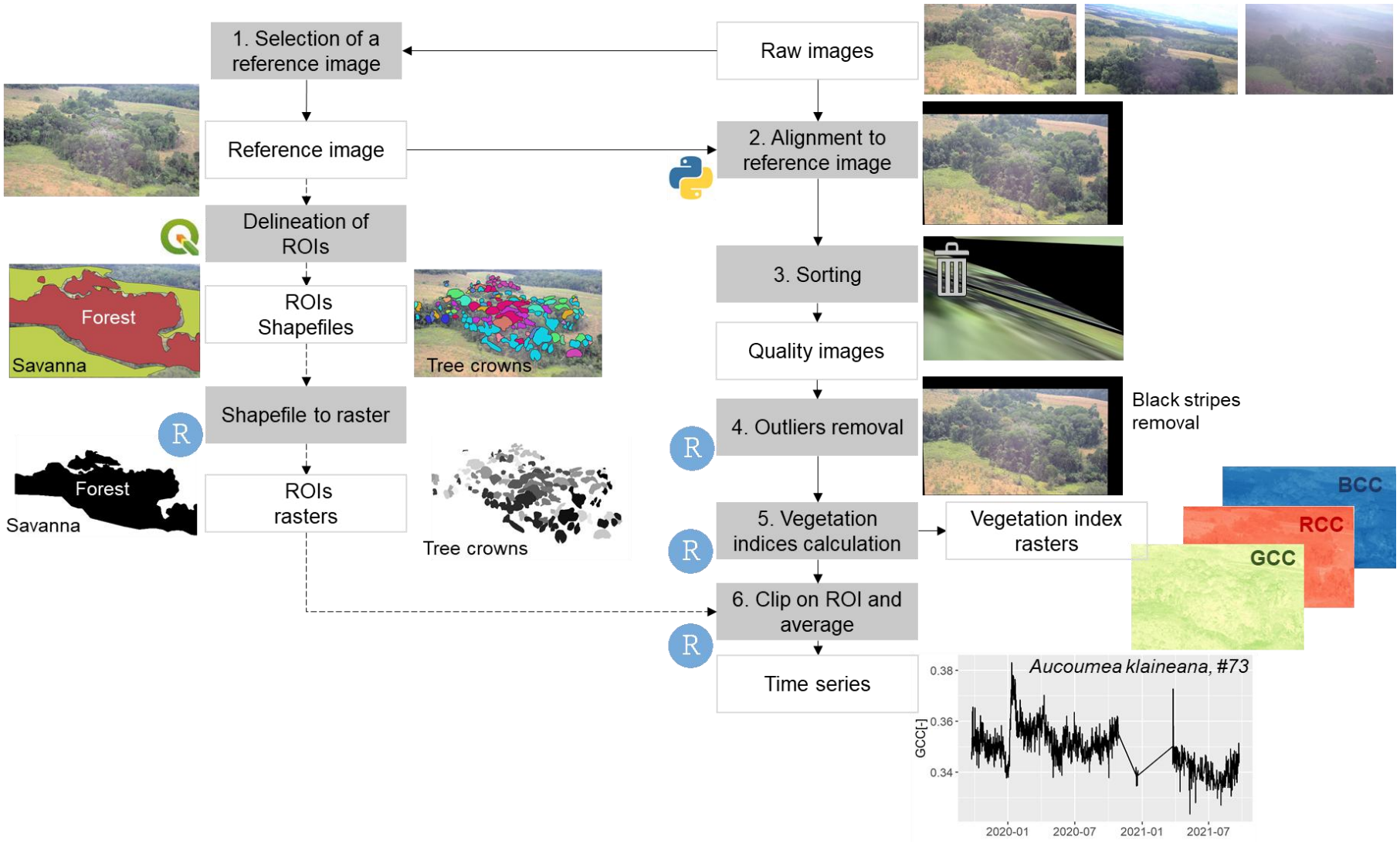

Figure 3. Variation of the Green Chromatic Coordinates (GCC, dimensionless) for the three phenocams, 005 (a), 006 (b) and 007 (c), installed at Lopé NP and for which a two-year time series is available. The reference images are shown as inset. The lines correspond to the predictions of a GAMM model fitted separately for the forest (green) and savanna (yellow) on the ROI average for each image (one cross). (d) Monthly cumulative rainfall amounts (in red) and daily average temperature (in blue) throughout time are presented in the style of a Walter-Lieth climate diagram. Dry seasons occur when the rainfall curve falls below the temperature curve (shown as the dotted red area, the start and end of the dry seasons are also indicated by a red vertical dotted line). Very wet periods occurs when the rainfall curve surpass 100 mm a month (in blue). The presence of savanna fires manually detected in the images is marked with a flame symbol. The interruptions in the timeseries are due to technical problems with the phenocams or with the weather station.