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Fenologia remota próxima e atributos foliares de vegetações sazonais

Relatório de Pós-doutorado realizado na Universidade Estadual Paulista (UNESP), Instituto de Biociências, Departamento de Biodiversidade, Rio Claro.

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Near-remote phenology and leaf traits of seasonal vegetations

Work Package 3 (WP3) of the NordEste project

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Postdoc: Dr. Desirée Marques Ramos

Post-doctoral Supervisor: Prof. Dr. L. Patrícia C. Morellato

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Abstract of the initial proposal

Drivers of leafing phenology are still unknown for several tropical system holding most of the global diversity of species. Remote sensing estimates leafing time over continental (satellite) and regional/local scales (digital cameras - near-surface phenology) by applying several greenness indices. Near-surface remote phenology using digital cameras enhances the temporal resolution of phenological information at individual tree, species, and community scale. The present project proposes to investigate, based on near-surface phenology, the proximate drivers of seasonal tropical plant phenology, i.e., which climatic factors are responsible for changes in leaf phenophases in two ecosystems: cerrado and caatinga. How climate affect the timing of leafing season in communities varying in their degree of seasonality and in time and length of growing (leafing) season? How is the timing of growth linked to plant physiology (i.e., which plant traits change first, e.g., water contents prior to mineral contents during leafing or before flowering)? Determine major plant phenology strategies based on leafing timing and leaf traits. How many functional groups are detected in the caatinga compared to cerrado?

1. Objectives of the Post-doc

Period of the Post-doc activities: 1st September 2017 - 31th December 2020.

The WP3 Post-doctoral fellowship in phenology started on 1st September 2017 and since then the research has been conducted in the field, processing data at laboratory and in the internship at Reading, UK (see Post-doc activities schedule, Table 1) working on activities related to the WP3 project, as well as additional activities related to the NordEste project WP1, WP5 and WP7 (see item 2).

The objective of the WP3 project was **to determine the leafing patterns of Caatinga tree species and their environmental drivers**. For this objective we applied the near-surface remote phenology approach, which consists of the usage of daily sequential repeated imagery taken with digital cameras to recognize annual leafing patterns. In each image it is possible to draw "Regions of Interest" (ROI) which are areas where the phenological index is estimated. The ROIs can be crowns of species from the community or the plot area, when the plot is in the camera's field of view (Figure 1). For each ROI in the image an index, known as normalized green chromatic coordinate (Gcc), can be

calculated based upon the three channel imaging sensors of the colors red, green, and blue (RGB). Changes in Gcc values are a reliable measurement of the changes in the leafing patterns, such as leaf flush and fall. Therefore, using cameras, it is possible to conduct finely resolved daily phenological observations of several individuals and plant species, providing adequate data frequency with which to understand the environmental triggers of leafing patterns in Caatinga vegetation.

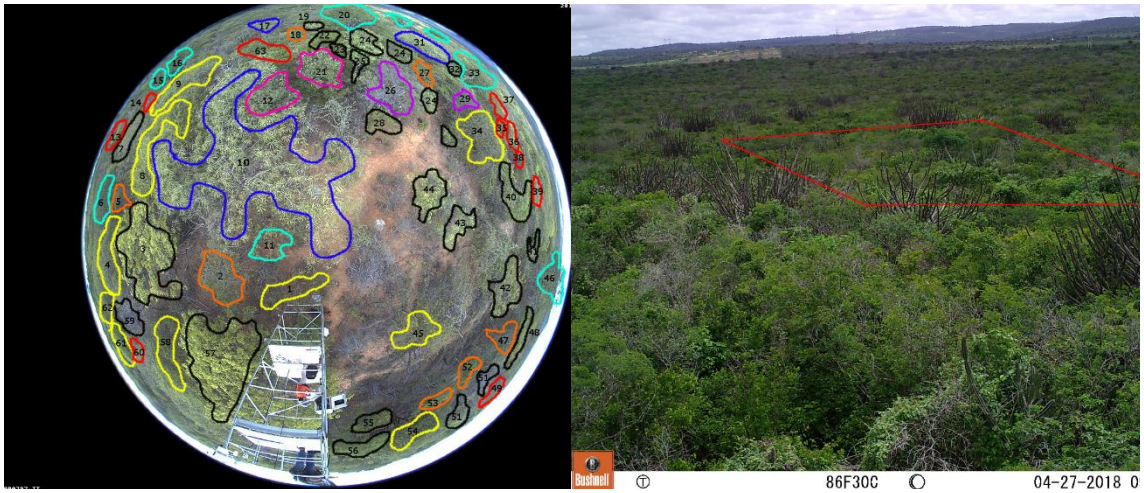


Figure 1. Types of camera perspectives used in the near-surface remote phenology approach. On the left it is an example of Mobotix camera's view (hemispherical lens, vertical orientation) from Serra Talhada. Each color represents tree crowns of individuals from the same species. On the right is an example of Bushnell camera's view (standard lens, landscape orientation) from Campina Grande with the plot area outlined in red.

2. Summary of the activities developed

2.1 Phenocam set up

The phenology work was focused on the set up of the totally new Phenocam Network in the Caatinga biome, distributed over the Northeastern region of Brazil. This new Phenocam Network will integrate the Phenocam Network from the e-phenology project funded by Fapesp-Microsoft: (http://www.recod.ic.unicamp.br/ephenology/client/index.html#/), which are distributed over the other Brazilian biomes. One digital hemispherical lens camera Mobotix Q 25 (Mobotix AG — Germany) was set up at the top of the flux towers in five sites. The towers are surrounded by native vegetation and the camera was positioned angled downward (180°), providing a hemispherical view of the trees' canopies following e-phenology protocol (Alberton et al. 2017). To have a direct measurement of the plot's leaf

production one Bushnell camera was set up on the ground level, in aluminium poles at 1.8 m high, providing a plot's view.

To encompass the climatic and vegetation structural variation present in the Caatinga, we set up the cameras at seven sites over a geographic range of NORDETE plots (see WP1, differing in precipitation regimes and floristic composition, including the transition areas between SDTF and Savanna vegetation (Fig. 2).

2.2 Field campaigns

Field campaigns are shown in green color and numbered from 1 to 8 in the schedule (Table 1). The field work of these campaigns was focused on the phenocam and plot set up and collaboration with floristic (WP1) and physiology (WP5) research activities. The activities developed in each field campaign are described below:

Field 1 – (Period: 16/11/2017 - 08/12/2017)

In this field I set up seven cameras for phenological observations in three sites at Pernambuco state: three bushnell cameras at Petrolina, one Mobotix and one Bushnell at Serra Talhada and one Mobotix and one Bushnell at São João. The Mobotix set up is time consuming due to the necessity to build aluminium cables and supports in the local cities, which are necessary to fix the camera in the tower.

Field 2 – (Period: 11/01/2018 - 09/02/2018)

In this field I did the identification of the tree's crowns of the individuals registered in the camera images for the phenology sampling in Petrolina, Serra Talhada and São João sites at Pernambuco state. It was possible to identify 9 tree species in Petrolina, 7 in Serra Talhada and 10 in São João. I also collaborated measuring species traits of trees, which includes specific leaf area, specific wood density and photosynthesis with Dr Raquel Miatto (WP5), another FAPESP pos-doctoral fellow of Nordesr project, in the same sites. Additionally, I collected the spectral reflectance trait of leaves for the same species. These traits are also important to explain the phenological patterns and will be correlated in future manuscripts in collaboration with the physiology research group (WP7) of the project.

Field 3 – (Period: 16/02/2018 - 05/03/2018)

In this field I participated in the two plot set ups in Macaúbas, BA and Manga, MG. I set up one Mobotix and one Bushnell cameras in Parque Lagoa do Cajueiro (Cajueiro), in Matias Cardoso, MG. I also collaborated measuring species traits of trees, which includes

specific leaf area, specific wood density and photosynthesis with Raquel Miatto in Macaúbas and Cajueiro sites.

Field 4 – (Period: 18/03/2018 - 12/04/2018)

I set up two Bushnell cameras in each site in Parque Nacional de Sete Cidades (PN7C) at Piripiri, PI, and Serra das Almas (SDA), CE. I conducted the species traits measurement at Parque Nacional da Serra da Capivara, PI. I participated in the plot set up in Serra das Almas (WP1). I also contributed to the voucher collection with the floristic team in three sites. We have collected in total 147 vouchers in PN7C, 36 in SDA and 36 in Buriti dos Lopes, PI.

Field 5 – (Period: 18/04/2018 - 07/05/2018)

I set up one Mobotix and one Bushnell cameras in Instituto Nacional do Semiárido (INSA) Campina Grande, PB. I participated in the plot set up in Mossoró, RN, Campina Grande, and Patos, PB sites. I also contributed to the voucher collection with the floristic team in these three sites (WP1). With the help of the floristic team, I did the identification of the individuals of nine species for the Bushnell camera image. We have collected in total 147 vouchers in 63 Mossoró, 68 in INSA and 88 in Patos.

Field 6 – (Period: 08/07/2018 - 14/07/2018)

It was not possible to conduct the identification of individuals in the last field campaign (Field 5) for one Mobotix camera, so a second field trip to INSA was planned for this goal. In this field trip I did the identification of individuals of 10 species of this camera. I also set up one more Bushnell camera and did the tree's crowns identification of seven species for this camera. Additional vouchers were collected and sent to the Herbário de Feira de Santana, BA to confirm the plant identifications in the field.

Field 7 – (Period: 09/12/2018 - 14/12/2018)

It was not possible to conduct the identification of individuals in the field campaign (Field 3) for one Mobotix camera, so a second field trip to Cajueiro was planned for this goal and to download data from the cameras. In this field trip I did the identification of individuals of 11 species of this camera.

Field 8 – (Period: 14/01/2019 - 22/01/2019)

This field trip was planned to download phenological data of Serra das Almas and Parque Nacional de Sete Cidades. I also collected root samples for anatomy with Ítalo Coutinho, a Professor and collaborator of the NordEste project.

2.3 Integration with other work packages

As planned in the main NordEste project, we are working in an integrative way with WP7 (modelling team) and WP5 (physiology team) work packages:

1) WP7 collaboration - We have provided the phenological data from Petrolina, Serra Talhada and São João sites to Rodolfo Nóbrega (post-doctoral fellow) and Anne Verhoef (Co-Pi NERC) to use in the modelling of carbon, water and energy fluxes of the Caatinga, and discussed haw to integrate that information in the Models.

2) WP5 collaboration – In collaboration with Raquel Miatto and Tomas Domingues we have included the specific wood density data as predictor of the phenology pattern of Caatinga tree species. I am leading the writing of the first PD manuscript "Leafing strategies of trees from Seasonally Dry Tropical Forests in relation to rainfall variability, *in prep*." in collaboration with several researchers of the NordEste project (see item 3.4; Appendix VII).

3) Collaboration with Rennan Paloschi and Laura Borma (INPE) - Climatic controls on tree water use patterns of woody Caatinga. We provided the phenology data which was used integrated with the analysis of sap flow seasonality of tree species from Serra Talhada site. The results of this collaboration were published in Remote Sensing "Environmental Drivers of Water Use for Caatinga Woody Plant Species: Combining Remote Sensing Phenology and Sap Flow Measurements" (see item 4.2; Appendix VI).

4) Collaboration with floristic team (WP1)- I also contributed to the plot set up, voucher collection, and tree identification with the floristic team in these three sites. The results of this collaboration were published in Plants People Planet "Expanding tropical forest monitoring into Dry Forests: The DRYFLOR protocol for permanent plots" (see item 4.2; Appendix V).

2.4 Data processing

I have processed the images of 14 cameras from five sites: Petrolina, Serra Talhada, São João, Campina Grande and Cajueiro, collected from 2017 to 2020. I have also processed leaf reflectance data from 115 individuals from 56 tree species of five sites: Petrolina, Serra Talhada, São João, Macaúbas and Cajueiro. Besides the advanced draft

included here, we propose the writing of two manuscripts integrating phenological, morphological and physiological traits, CO_2 flux and reflectance data (items 3.5 and 3.6). However, we expected at least four more papers integrating topics from NORDESTE project (see item 3.3).

Table 1. Schedule of activities during the Post-doc period.

Activities	Year/Bimester																			
	2017	2018							2019						2020					
	1	2	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Cameras acquisition and field planning																				
Field campaigns across Nordeste sites		1	2, 3	4	5	6		7	8											
Data processing, organization and analysis																				
Writing scientific report for the project and BEPE proposal																				
BEPE-Internship																				
EGU Conference in Vienna																				
Writing scientific report for BEPE for the project																				
NordEste Meeting at Fortaleza, CE																				
Maternity leave																				
Writing two papers in collaboration (see items 2.3 and 4.2)																				
Writing 1st manuscript draft (see item 3.4)																				
Writing the Final Report																				

3. Summary of the main results

3.1 The Northeast Phenocam Network: Species sampled

The main field activities planned for the WP3 were to set up phenocams and identify tree crowns in the images. Thus, in the field campaigns, from November 2017 to January 2019, we have set up 18 cameras (5 Mobotix, 13 Bushnell) in **seven sites** varying in environmental and climatic conditions (Table 2, Figure 2). There was a large variation in the average annual precipitation regimes, ranging from 387 mm to ~800 mm in sites located in SDTF biome and 1400 mm in sites located in savanna biome (Table 2). In five sites, the cameras were placed in towers equipped with climatic stations to provide associated environmental data, including precipitation, air temperature, and humidity. We identified ROIs (crowns) of **313 individuals from 45 tree species** at five sites. The species identification at two sites were scheduled to 2020 growing season. Unfortunately, the COVID19 pandemic suspended the field activities and we were unable to perform the necessary field trips to conclude plant identification. The number of species sampled varied between sites, from 7 to 17 species (Table 2). In general, it was possible to sample the most abundant species occurring in the plots at each site.

We registered the phenology pattern during two complete growing seasons from 2017 to 2020 at the supersites Petrolina, Serra Talhada and São João, extracted the GCC indices therein, and we provide a **draft of the first manuscript** (see item 3.3).

3.2 The Northeast Phenocam Network: Sites description

Sites in SDTF biome

Super sites (bold) – Sites with flux towers and where NORDESTE project concentrated collection of phenology, ecophysiology, functional and spectral data.

Petrolina (PET) is a protected area from the Brazilian Agricultural Research Corporation (Embrapa) named Embrapa Semiárido, located at Petrolina municipality and 395 m altitude asl. The mean annual total precipitation is 387 mm with more than 10 month dry season (Souza et al. 2016), and average annual temperature is 26.8 °C (Xavier et al. 2016). The main class of soil is acrisol and the area has been protected from grazing and anthropic disturbs during the last 40 years. The vegetation is a scrubland composed by trees of ~4.5m high with an open canopy (~35%) over an herbaceous stratum dominated

by bromeliads and shrubs. The dominant tree species are *Cenostigma microphyllum*, *Commiphora leptophloeos*, *Handroanthus spongiosus*, *Sapium glandulusom* and *Senegalia piauhiensis.*

Serra Talhada (STA) is a private area located at Serra Talhada municipality at 467 m altitude asl. The mean annual total precipitation is 574 mm, with 10 dry months and average annual temperature 24.1 °C (Souza et al. 2016, Xavier et al. 2016). The main class of soil is calcisol and the area is grazed by cattle and goats during the rainy season. The vegetation is composed mainly by trees of 5.3m high with an open canopy (~45%). The dominant tree species are *Cenostigma pyramidalis, Aspidosperma pyrifolium, Mimosa tenuiflora* and *Anadenanthera colubrina* var. cebil.

São João (SJO) is a private area located at Garanhuns municipality and 762 m altitude asl. The mean annual total precipitation is 800mm and 9.5 dry months (Souza et al. 2016), and average annual temperature is 22.8 °C (Xavier et al. 2016). The main class of soil is arenosol and the area is grazed by cattle and goats during the entire year. The vegetation is composed mainly by trees of 5.2m high with an open canopy (~45%). The dominant tree species are *Commiphora leptophloeos, Mimosa opthalmocentra, Pilosocereus* sp., *Sapium* sp., *Senegalia* sp. and *Spondias tuberosa*.

Campina Grande (CGA), the site is located at Instituto Nacional do Semiárido (INSA), a protected area, located at Campina Grande municipality, PB state and 493 asl. The mean annual total precipitation is 777mm and 5 dry months and the average annual temperature is 23.5 °C. The area has been protected from grazing and anthropic disturbs during the last 10 years. The vegetation is a scrubland composed by trees of ~5.3m high with an open canopy (~50%) over an herbaceous stratum dominated by bromeliads and shrubs. The dominant tree species are *Aspidosperma pyrifolium, Cenostigma pyramidale, Commiphora leptophloeos, Combretum* sp., *Senegalia sp.* and *Croton blanchetianus*.

Parque Loagoa do Cajueiro (CAJ) is a conservation area, located at Matias Cardoso municipality, MG state and 462 asl. The mean annual total precipitation is 818mm and 5 dry months and the average annual temperature is 24 °C (Pezzini et al. 2014). There are two distinct vegetation in the area and we set up one Mobotix camera in the first and one Bushnell camera in the second. The vegetation in the first area is a tall forest composed by trees of ~13m high with a closed canopy (~85%). The dominant tree species are *Poincianella pluviosa, Anadenanthera colubrina, Myracrodruon urundeuva* and *Plathymenia reticulata.* The vegetation in the second area (plot area) is an open scrubland SDTF (carrasco) composed by trees of ~4m high with an open canopy (~30%). The dominant tree species are

Aspidosperma pyrifolium, Callisthene microphylla, Cenostigma macrophyllum, Guapira tomentosa, Mimosa arenosa, Poecilanthe ulei, Pterocarpus rohrii, Ptercocarpus emarginatus and *Terminalia fagifolia*.

Reserva Particular do Patrimônio Natural Serra das Almas (SDA) is a conservation area, located at Crateús municipality, CE state. The mean annual total precipitation is 738mm and 7 dry months and the average annual temperature is 27.4 °C. There are two plots in the area and we set up one Bushnell camera each. The vegetation in the in the first plot is a SDTF vegetation composed trees of ~5.4m high with an open canopy (~55%). The dominant tree species are *Agonandra brasiliensis, Croton argyrophyllus, Eugenia dysenterica, Eugenia strictopetala, Guapira graciflora, Hymenaea eriogyne, Hymenaea velutina, Pityrocarpa moniliformis* and *Senegalia polyphylla*. The vegetation in the second plot is a SDTF composed by tall tree species of ~7m high with closed canopy (~85%). The dominant tree species are *Anadenanthera colubrina, Bauhinia cheilantha, Cenostigma nordestinum, Combretum leprosum, Cordia oncocalyx, Croton blanchetianus* and *Mimosa caesalpiniaefolia*.

Site in the transition area between SDTF and Cerrado

The last site, Parque Nacional de Sete Cidades (PN7C), is a conservation area, located at Piripiri municipality, PI state and 258 asl. The mean annual total precipitation is 1423mm and 5 dry months and the average annual temperature is 27.4 °C. There are two plots in the area and we set up one Bushnell camera each. The vegetation in the first plot is a typical savanna (cerrado sensu stricto) vegetation composed by an herbaceous layer with scattered trees of ~5.15m high with an open canopy (~30%). The dominant tree species are *Bowdichia virgilioides, Byrsonima crassifolia, Plathymenia reticulate, Psidium myrsinites, Qualea grandiflora, Qualea parviflora* and *Terminalia fagifolia*. The vegetation in the second plot is a mixture of mostly dense savanna (cerradão) composed by tall tree species of ~7.5m high with closed canopy (~70%) and a small portion of typical savanna (cerrado sensu stricto) with an open canopy (~40%). The dominant tree species are *Astrocaryum vulgare, Brosimum* sp., *Byrsonima* sp., *Casearia ulmifolia, Combretum fruticosum, Ephedranthus* sp., *Fridericia celastroides, Guapira* sp. and *Qualea grandiflora*.

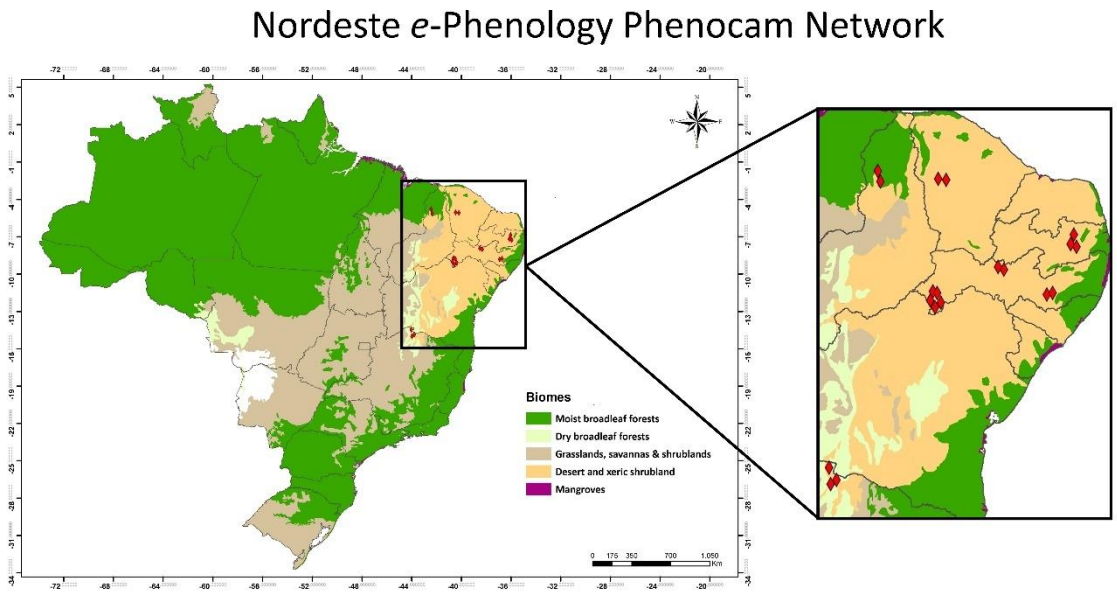


Figure 2. Distribution of the Northeast Phenocam Network across the Caatinga vegetation. On the right, outlined in black, is the Caatinga vegetation in detail. Red points refer to the cameras set up. Map modified from Olson et al. 2011. Desert and xeric shrubland = Caatinga biome.

3.3 Prospective papers and potential journals

Ramos et al. Leafing strategies of trees from Seasonally Dry Tropical Forests: the importance of rainfall variability. To be submitted to Journal of Vegetation Science. Item 3.4.

Ramos et al. Phenological and CO_2 flux patterns of seasonally dry tropical forests. To be submitted to American Journal of Botany. Item 3.5.

Ramos et al. Leaf reflectance and functional traits of trees from seasonally dry tropical forest. To be submitted to Remote Sensing of Environment. Item 3.6.

Ramos et al. Leafing exchange patterns and drivers across seasonally dry tropical forest. To be submitted to Journal of Ecology.

Nóbrega et al. Ecosystem total LAI partitioning in a seasonally dry tropical forest
To be submitted to Methods in Ecology and Evolution.

Nóbrega et al. Using terrestrial ecosystem modelling to improve our understanding of drought survival strategies of a dry neotropical forest in Brazil (Caatinga). To be submitted to New Phytologist.

Miatto et al. Trade-offs of Caatinga plants under contrasting soil types and precipitation regimes and a further comparison to other Brazilian biomes. To be submitted to Functional Ecology.

Miatto et al. Temperature response of photosynthesis across caatinga tree species. To be submitted to Functional Ecology.

Table 2. Number of species with crowns identified in the images and phenocam distribution across Caatinga sites with their environmental characterization

Site	State	Camera type	Lat.	Long.	Altitude (m)	Precipitation (mm)	Vegetation	Camera Type	Species (N)
Serra Talhada	PE	Mobotix	S 7.968171	W 38.384169	467	574	SDTF	LV	7
		Bushnell						PV	-
São João	PE	Mobotix	S 8.809972	W 36.405638	762	800	SDTF	LV	10
		Bushnell						PV	-
Petrolina	PE	Mobotix	S 9.046542	W 40.321278	395	387	SDTF	LV	17
		Bushnell 1						PV	-
		Bushnell 2						LV	NI
		Bushnell 3						LV	9
		Bushnell 4						LV	NI
Campina Grande	PB	Mobotix	S 7.280389	W 35.976307	493	777	SDTF	LV	11
		Bushnell 1						LV	9
		Bushnell 2						LV	7
Parque Nacional de Sete Cidades	PI	Bushnell 1	S 04.13662	W 41.72010	258	1423	Savanna	LV	-
		Bushnell 2	S 04.13424	W 41.68349	238		Savanna/SDTF	LV	-
Serra das Almas	CE	Bushnell 1	S 05.14654	W 40.92813	690	738	SDTF	LV	-
		Bushnell 2	S 05.11708	W 40.87311	300			LV	-
Cajueiro	MG	Mobotix	S 14.93099	W 43.92202	462	818	SDTF	LV	11
		Bushnell 1	S 14.96410	W 43.91666	467			LV	-

LV = Landscape view; PV = Plot view; NI = Not identified; - = Not possible to identify.

3.4 Manuscript draft

Leafing strategies of trees from Seasonally Dry Tropical Forests: the importance of rainfall variability

Complete manuscript in Appendix VII.

3.5 Manuscript proposal 1

Phenological and CO_2 flux patterns of seasonally dry tropical forests

Questions:

1) What is the contribution of leaf phenology (GCC) in carbon dioxide (CO_2) fluxes, measured as net ecosystem exchange (NEE) and gross primary productivity (GPP) across a gradient of rainfall seasonality in Caatinga vegetation?
2) What is the reliability of satellite remote sensing vegetation indices (VIs) to determine phenological transition dates in the strongly seasonal Caatinga vegetation when compared to the VI (GCC) derived from the near-surface remote sensing (phenocam)? What is the correspondence between the satellite and phenocam VIs?

Methods

Study area

Caatinga vegetation is the largest SDTF in the New World, occurring mainly in the Northeastern Brazil under a semi-arid climate (Köppen's BSh). We study five areas in Caatinga across a gradient of mean annual rainfall: Petrolina (PET; 340 mm), Campina Grande (CGR; 550 mm), Serra Talhada (STA; 620 mm), São João (SJO; 620 mm) and Cajueiro (CAJ; 818 mm). PET, STA and SJO are located at Pernambuco (PE) State, CGR at Paraíba (PB) State and CAJ at Minas Gerais (MG) State.

Petrolina (PET): The first site is a protected area from the Brazilian Agricultural Research Corporation (Embrapa, Semiarid unit), located at Petrolina municipality (9.0480° S, 40.3198° W) at 395 m a.s.l. The area has been protected from grazing and anthropic disturbs during the last 40 years. The most common soil is Acrisol and the vegetation is a scrubland composed of trees with average height of ~4.5 m and tree density of approximately 500 individuals ha^{-1} over an herbaceous and shrubby stratum dominated by

bromeliads. The dominant tree species are *Senegalia polyphylla*, *Manihot* sp., *Cenostigma microphyllum*, *Sapium glandulusom Handroanthus spongiosus* and *Commiphora leptophloeos*. Together, these species account for 88% of the total relative abundance of trees in the area.

Serra Talhada (STA): The second site is an experimental area located at Serra Talhada municipality (7.97008° S; 38.3849° W) at 467 m a.s.l. The area is grazed by cattle and goats during the rainy season. The main class of soil is Calcisol and the vegetation is mainly composed of trees with average height of ~5 m and tree density of approximately 780 individuals ha^{-1}. The dominant tree species are *Aspidosperma pyrifolium*, *Cenostigma nordestinum, Senegalia polyphylla* and *Anadenanthera colubrina* var. *cebil*. Together, these species account for 79% of the total relative abundance of trees in the area.

São João (SJO): The third site is an experimental area surrounded by agricultural lands located at São João municipality (8.80967°S; 36.4054°W), at 762 m a.s.l. The area is grazed by cattle and goats during the entire year. The most common soil is Arenosol and the vegetation is mainly composed of trees with average height of ~5 m and tree density of approximately 670 individuals ha^{-1}. The dominant tree species are *Pilosocereus pachycladus*, *Commiphora leptophloeos*, *Mimosa tenuiflora*, *Piptadenia flava*, *Lippia origanoides* and *Sapium glandulosum*. Together, these species account for 71% of the total relative abundance of trees in the area.

Campina Grande (CGA): The fourth site is a protected area from the Instituto Nacional do Semi-Árido (INSA) located at Campina Grande municipality (7.280389° S; 35.976307° W) at 493 m a.s.l. The area has been protected from grazing and anthropic disturbs during the last 10 years. The main class of soil is sandy loam and the vegetation is mainly composed of trees with average height of ~5.1 m and tree density of approximately 675 individuals ha^{-1}. The dominant tree species are *Cenostigma pyramidale*, *Combretum monetaria*, *Aspidosperma pyrifolium*, *Manihot* sp. and *Piptadenia flava*. Together, these species account for 71% of the total relative abundance of trees in the area.

Parque Loagoa do Cajueiro (CAJ): the fifth site is a conservation area, located at Matias Cardoso municipality, MG state and 462 asl. The mean annual total precipitation is 818mm and 5 dry months and the average annual temperature is 24 °C (Pezzini et al. 2014). There are two distinct vegetation in the area and we set up one Mobotix camera in the first and one Bushnell camera in the second. The vegetation in the first area is a tall forest

composed by trees of ~13m high with a closed canopy (~85%). The dominant tree species are *Poincianella pluviosa, Anadenanthera colubrina, Myracrodruon urundeuva* and *Plathymenia reticulata*. The vegetation in the second area (plot area) is an open scrubland SDTF (carrasco) composed by trees of ~4m high with an open canopy (~30%). The dominant tree species are *Aspidosperma pyrifolium, Callisthene microphylla, Cenostigma macrophyllum, Guapira tomentosa, Mimosa arenosa, Poecilanthe ulei, Pterocarpus rohrii, Ptercocarpus emarginatus* and *Terminalia fagifolia*.

Near-surface phenological measurements

Camera set-up - We used 14 cameras in this study, five digital hemispherical lens cameras Mobotix, Q25 (Mobotix AG — Germany; for detailed information on the usage of Mobotix cameras for phenological observations, see Alberton et al. 2017), placed in vertical downward (180°) orientation and nine digital standard lens cameras Bushnell, Trophy Cam HD Essential E3 (Bushnell — EUA), placed in landscape orientation. One Mobotix camera was placed on towers in PET (10 m high), STA (10 m high), SJO (10 m high), CGA (13 m high) and CAJ (18 m high). Excepting in CAJ, all sites have CO_2 and water flux measurements. The Mobotix cameras were placed with an average distance of 10 m above from the vegetation canopies (Fig. 2). The energy supply of Mobotix cameras comes from a system composed by a 12 V battery charged by solar panels while Bushnell cameras are charged by AA lithium batteries.

We set up four Bushnell cameras in PET: two placed on the top of the tower (17.5 m high), one positioned to East and the other to West; one on-the-ground, mounted on a pole (1.8 m high), resulting in a near view of the vegetation (Fig. 3) and the last one on the tower in the same high (10 m high) and with a similar field of view of the Mobotix camera. Since the Bushnell cameras are trail cameras designed for fauna video or photo recording and, as far as we know, this is the first study to apply it for plant phenological observations, we placed this Bushnell camera (10 m high) next to the Mobotix, to compare the possible influences of the camera type over the phenological indices. We also set up one Bushnell camera on-the-ground, as in PET, mounted on a pole (1.8 m high) at STA and SJO, resulting in a near view of the vegetation. Two Bushnell cameras were set up on the top of the tower (13 m high) in CGA, positioned one to East and the other to Northwest.

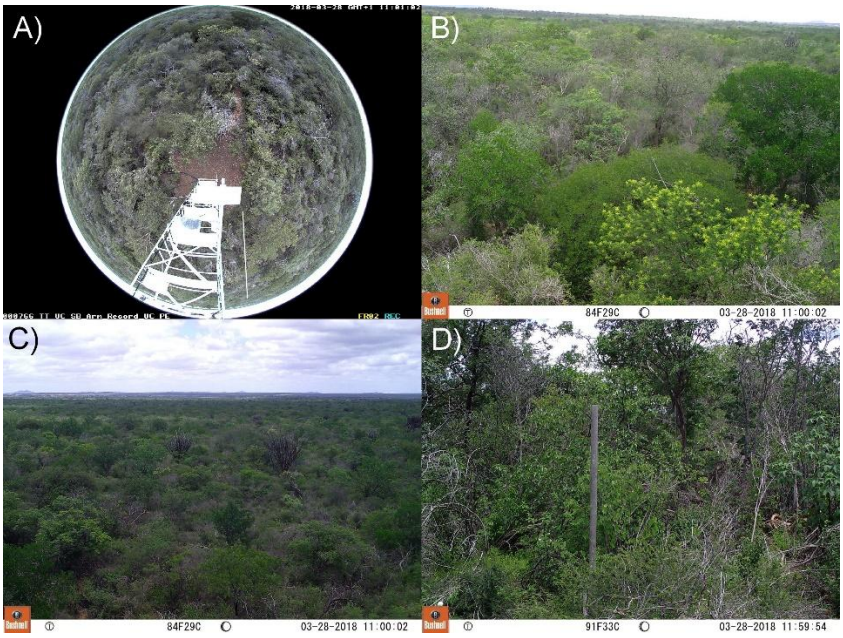


Figure 3. Examples of field of views of cameras types and set-up positions in the site of Petrolina, PE. (a) Mobotix – tower, 11 m high; (b-c) Bushnell – tower, 11 m and 17.5 m high; and (d) Bushnell – on-the-ground, 2 m high. The same day of the year (DOY) 87, 2018 is shown in the four images.

Image acquisition and processing

Cameras were programmed to take daily images, varying from three to four images, in the first five minutes of each hour, from 06:00 am to 06:00 pm (UC-3; Universal Time Coordinated). Images were taken in JPEG format with 1280 x 960 pixels of resolution (Alberton et al. 2017). The leafing patterns were registered during one to three growing seasons from 2017 to 2020, with different starting and ending dates depending on the site or camera: PET, 01/11/2017 to 31/12/2020; STA, 28/11/2017 to 31/12/2020; CGA, 28/11/2017 to 31/12/2020; SJO, 20/12/2017 to 03/05/2020 and CAJ, 04/03/2018 to 24/11/2020.

Images with blocked field of view, with excessive fog or too dark, for example, were excluded of the analysis. To represent the plant community of each site, we drawn a Region of Interest (ROI) in the images which consisted of the selection of the entire vegetated area but excluding the bare ground, the tower area (for the Mobotix images) and the borders of the image. The digital numbers (DNs) red, green and blue color channels

(RGB) were extracted from the JPEG images for each community ROIs across all the images on given day. The total RGB DN was calculated as in Eq. 1 (see Richardson et al. 2009). Then, the normalized Green Chromatic Coordinate index (Gcc; see Alberton et al. 2017; Richardson et al. 2009) was calculated as the ratio of the relative brightness of the green color channel (green DN) over the total DN brightness, as in Eq. 2:

Total RGB DN = red DN + green DN + blue DN (1)

$$\text{Green \%} = \frac{\text{Green DN}}{\text{Total RGB DN}} \quad (2)$$

To deal with the variation in the Gcc values we used the 90th percentile method proposed by Sonnentag et al. (2012), however, we applied the 90th percentile to the photos of the entire day and to the mid-day photos (from 10:00 am to 16:00 pm), and we found less variation in the Gcc values of the mid-day photos. Thus, we used the daily values of the 90th percentile calculated from the mid-day photos instead of the three days window moving average proposed by Sonnentag et al. (2012), due to the fast response of the Caatinga vegetation to low rainfall events (Machado et al. 1997; Alberton et al. 2019; Paloschi et al. 2021).

Phenocam phenological metrics

We used the Gcc to calculate the phenological transition dates for each growing season of each site by applying the methodology proposed by Alberton et al. (2019) and also applied in Paloschi et al. (2021). The phenological transition dates were: start of growing season (SOS), end of growing season (EOS) and length of growing season (LOS). The LOS is calculated as the difference between the EOS and SOS dates for each growing season. We visually inspected the images to verify if the transition dates SOS and EOS were a reliable representation of the phenological status of the vegetation. For this, we considered as SOS date when <70% of the ROI was with leaves or leafless for the EOS date. The transition dates were adjusted after the visual inspection, when necessary. For the calculation of the transition dates, we used the Gcc data of the camera with more observations for each site, the Mobotix cameras for PET, SET and SJO and the Bushnell Northwest for CGA. When the transition date occurred in a moment with absence of images, we used the images of other camera, when they were present, to confirm the date.

Preliminary phenological results:

We measured the length of growing season from 2017 to 2020, which encompass two to three growing seasons, depending on the site (Table 3; Figs. 4-8). The LOS of Caatinga sites were highly variable, ranging from 189 to 292 days of duration (Table 3). Unexpectedly, the LOS of plant communities did not to show a pattern related to the average rainfall across sites. For example, the LOS was the longest (292 days), during the growing season of 2019, for the plant community of CGA site, the second driest site, while the LOS was the shortest (189 days), during the year of 2018 for the SJO site, the wettest among the sites (Table 3).

Table 3. Phenological transition dates, start of growing season (SOS), end of growing season (EOS) and length of growing season (LOS) calculated for the Caatinga vegetation of Petrolina, Serra Talhada, São João and Campina Grande.

Site/Growing season	SOS_Phenocam (DOY)	EOS_Phenocam (DOY)	LOS_Phenocam (Days)
Petrolina			
2017-2018	350	178	193
2018-2019	302	180	243
2019-2020	12	220	208
2020-2021	316		
Serra Talhada			
2017-2018	363	237	241
2018-2019	339	235	261
2019-2020	341	252	276
2020-2021	314		
São João			
2018	24	229	205
2019	28	276	248
2020	40		
Campina Grande			
2018		248	
2019	33	325	292
2020	62	291	229

The vegetation of all sites shown a markedly seasonal leaf flushing during the rainy season and leaf fall during the dry season (Figs. 4-8). We are still compiling and processing

the climatic data that will be analysed together with phenological indices from cameras (Gcc) and satellite (EVI, NDVI among other).

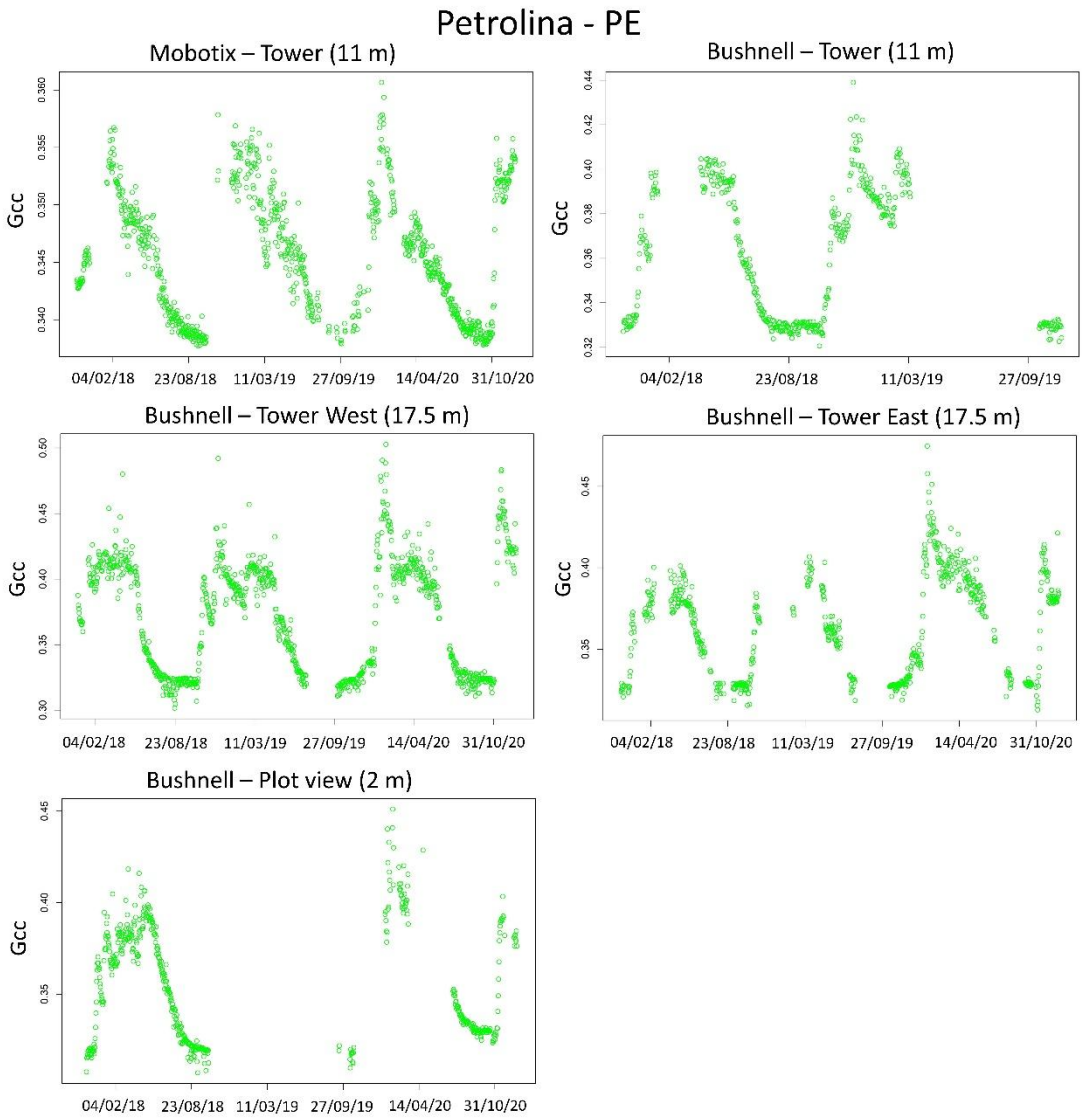


Figure 4. Values of Gcc time series for the community of Petrolina site showing different camera types, Mobotix and Bushnell and the tower and on-the-ground field of views. Gcc values corresponds to the 90th percentiles calculated for the Gcc extracted from the images of the mid-day hours (from 10:00 to 14:00 hours).

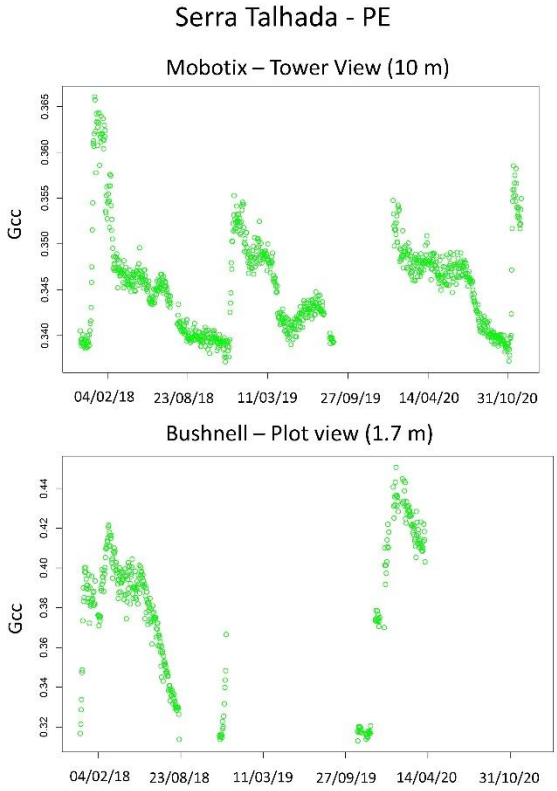


Figure 5. Values of Gcc time series for the community of Serra Talhada site showing different camera types, Mobotix and Bushnell and the tower and on-the-ground field of views. Gcc values corresponds to the 90th percentiles calculated for the Gcc extracted from the images of the mid-day hours (from 10:00 to 14:00 hours).

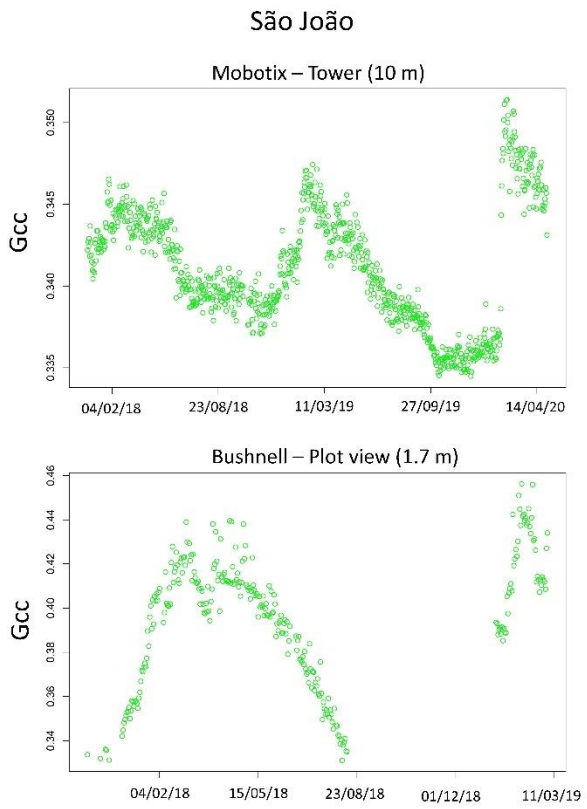


Figure 6. Values of Gcc time series for the community of São João site showing different camera types, Mobotix and Bushnell and the tower and on-the-ground field of views. Gcc values corresponds to the 90th percentiles calculated for the Gcc extracted from the images of the mid-day hours (from 10:00 to 14:00 hours).

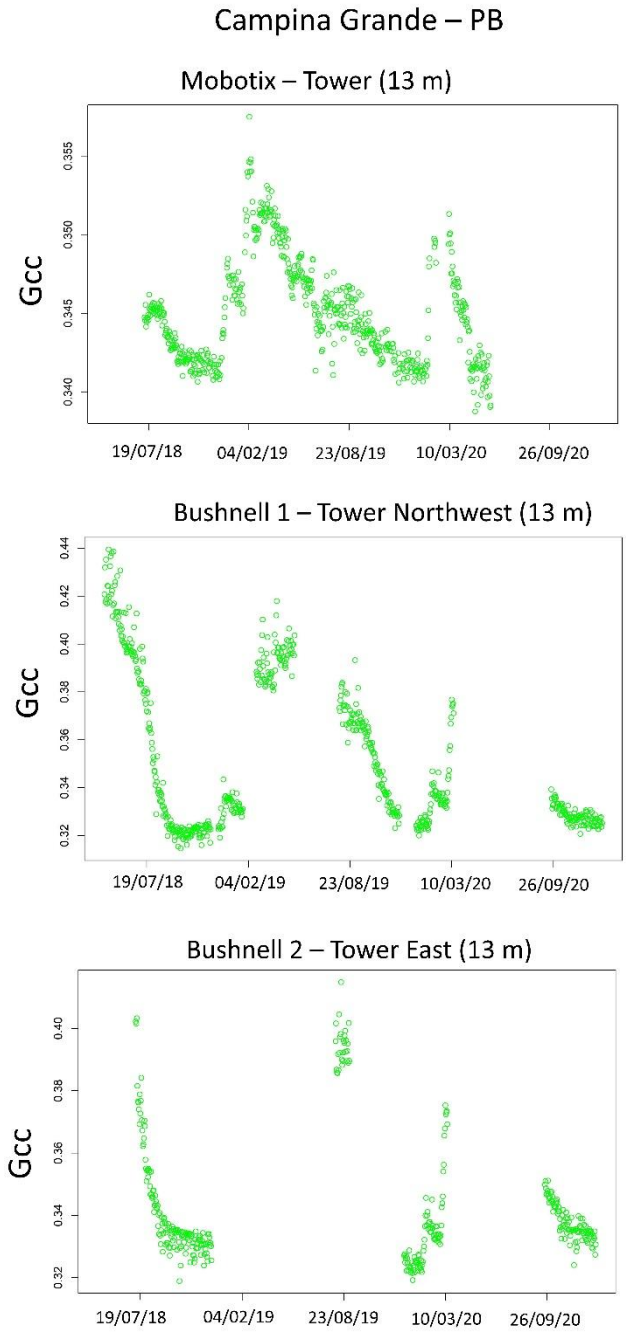


Figure 7. Values of Gcc time series for the community of Campina Grande site showing different camera types, Mobotix and Bushnell and the tower field of view. Gcc values corresponds to the 90th percentiles calculated for the Gcc extracted from the images of the mid-day hours (from 10:00 to 14:00 hours).

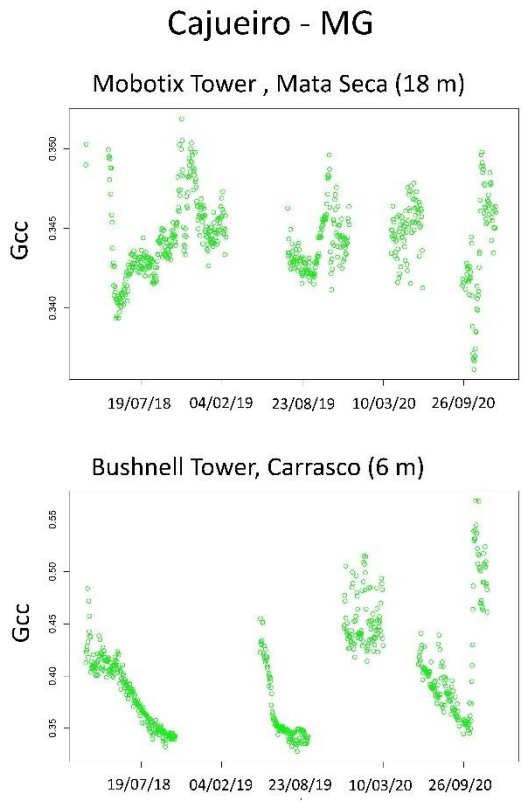


Figure 8. Values of Gcc time series for the communities of Cajueiro site showing different camera and vegetation types. Mobotix in Mata seca vegetation and Bushnell in Carrasco vegetation. Gcc values for the mobotix camera corresponds to the 90th percentiles calculated for the Gcc extracted from the images of the mid-day hours (from 10:00 to 14:00 hours) while for Bushnell camera the values for all daily hours were used (from 06:00 to 18:00 hours).

3.6 Manuscript proposal 2

Leaf reflectance and functional traits of trees from seasonally dry tropical forest

Leaf reflectance spectra are phylogenetic conservative traits that can be used to assess the diversity of species from plant communities (Meireles et al. 2020). Different ranges of the spectrum represent how leaf components absorb light: chlorophyll and carotenoids absorb light in the visible range 400-700 nm, while water, lignin and cellulose absorb light in the near-infrared 700-1100 nm ranges (Asner et al. 2014; Meireles et al. 2020). Because tree species have different strategies associated to their investment in water use and structural components, we expect to find differences in leaf reflectance related to

functional types related to water economy strategy and, consequently in phenological strategy (Streher et al., 2020). We also expect that leaf reflectance will integrate and better represent functional traits across species and Caatinga vegetation types.

Questions:

1)What are the key spectral functional group of species across Caatinga vegetation?

2) Is leaf reflectance a reliable measurement to integrate functional trait variability across Caatinga tree species?

Methods

We collected spectral reflectance of 115 individuals from 56 tree species in five sites across the Caatinga vegetation. We collected ten leaves from one to five individuals per species (Table 4; Figure 9). Fully developed and mature leaves exposed to the sun were collected for this analysis. Leaves were collected in the field and kept in plastic bags inside of a cooler to avoid water loss for about 5 to 8 hours until measurements were conducted. The leaf reflectance measurements were taken at room conditions using a full-range (350–2500 nm) ASD FieldSpec 4 Standard spectroradiometer (Analytical Spectral Devices, ASD, Malvern, Worcestershire, UK), with a spectral resolution of 3 nm in the VNIR and 10 nm in the SWIR, and wavelength accuracy of 0.5 nm. Leaf reflectance measurements were taken by placing the ASD leaf probe accessory at 90° perpendicular to the leaf, placed over a black non-reflective surface (Streher et al. 2020). Ten measurements were taken for each leaf in the adaxial surface.

Morphological (leaf mass per area, LMA and leaf dry mater content, LDMC) and physiological (water content) traits were also measured for the same leaves. Leaf phenological patterns (start of growing season SOS, end of growing season EOS and length of growing season) were also registered for most of species used in the leaf reflectance measurements.

Analysis

We are going to apply the partial least square regression (PLSR) models to predict LMA, LDMC and water content from leaf spectral properties (Streher et al., 2020).

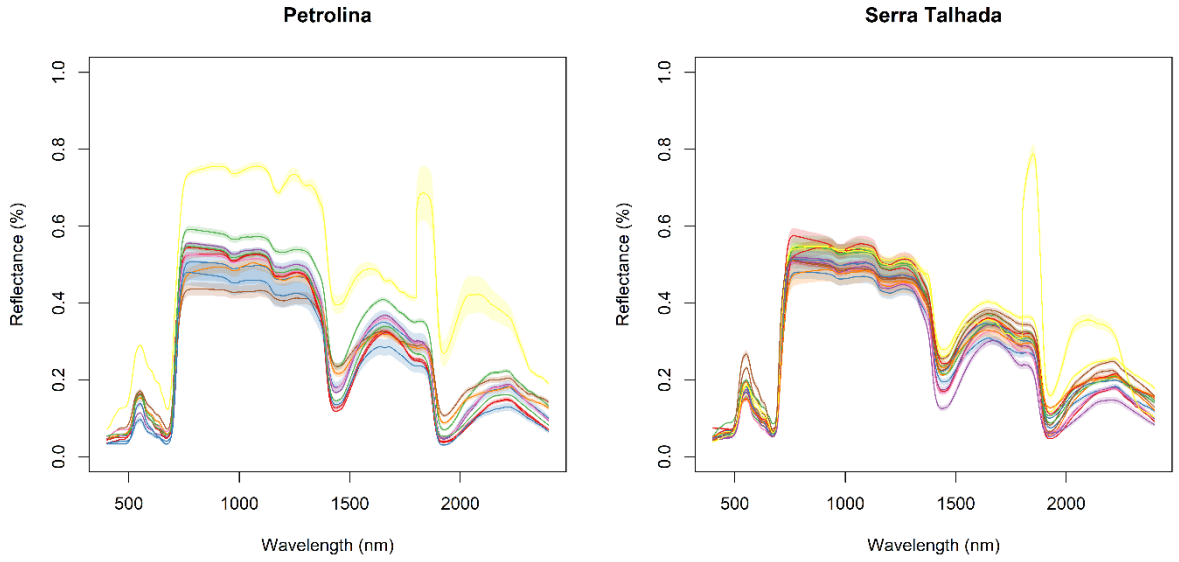
Preliminary reflectance results:

Table 4. Number of individuals and species sampled for the leaf reflectance measurements in five sites across Caatinga vegetation.

Species	Site/Individuals				
	PET	STA	SJO	MCB	CAJ
Amburana cearensis		2		1	
Anadenanthera colubrina		2		2	2
Anaxagorea dolichocarpa					1
Annona sylvatica		1			
Annona vepretorum				1	
Aspidosperma pyrifolium	3	2			3
Aspidosperma sp1				1	
Bauhinia cheilantha		1			
Callisthene microphylla					4
Cenostigma bracteosum				1	
Cenostigma macrophyllum					2
Cenostigma microphyllum	3				
Cenostigma nordestinum		3			
Cochlospermum vitifolium				1	
Cocoloba schwackeana				1	
Combretum leprosum					1
Commiphora leptophloeos			1	1	
Croton conduplicatus	1				
Croton grewioides				1	
Cynophalla flexuosa			1		
Erythroxylum pungens		3			
Fraurofera multiflora				3	
Guapira laxa			1		
Guapira tomentosa					2
Handroanthus selachidentata				1	
Handroanthus spongiosus	3				
Jatropha mutabilis				2	
Kielmeyera speciosa					1
Lachesiodendron viridiflorum	2				
Luetzelburgia auriculata				2	
Manihot carthagenensis		2			
Manihot pseudoglaziovii	3				
Manihot sp4				1	
Mimosa acutistipula		5			
Mimosa ophthalmocentra				1	
Mimosa ostilis				1	
Muellera campestris					1
Myracrodruon urundueva		1			
Piptadenia flava		2			
Pityrocarpa moniliformis					1
Platypodium elegans					1
Poecilanthe ulei					2
Pseudobombax simplicifolium	1			2	
Pterocarpus violaceus				1	

Pterodon emarginatus					3
Rubiaceae sp4				1	
Sapium glandulosum	3	2			
Sarcomphalus joazeiro		1			
Schinopsis brasiliensis	1				
Senegalia polyphylla	2	1			
Senna macranthera				2	
Sideroxylon obtusifolium		1			
Spondias tuberosa	2		1	2	
Swartzia macrostachya					1
Talisia esculenta			1		
Terminalia fagifolia				1	2

Study sites: PET, Petrolina - PE; STA - PE, Serra Talhada - PE; SJO, São João - PE; MCB, Macaúbas - BA and CAJ, Cajueiro State Park at Matias Cardoso – MG.



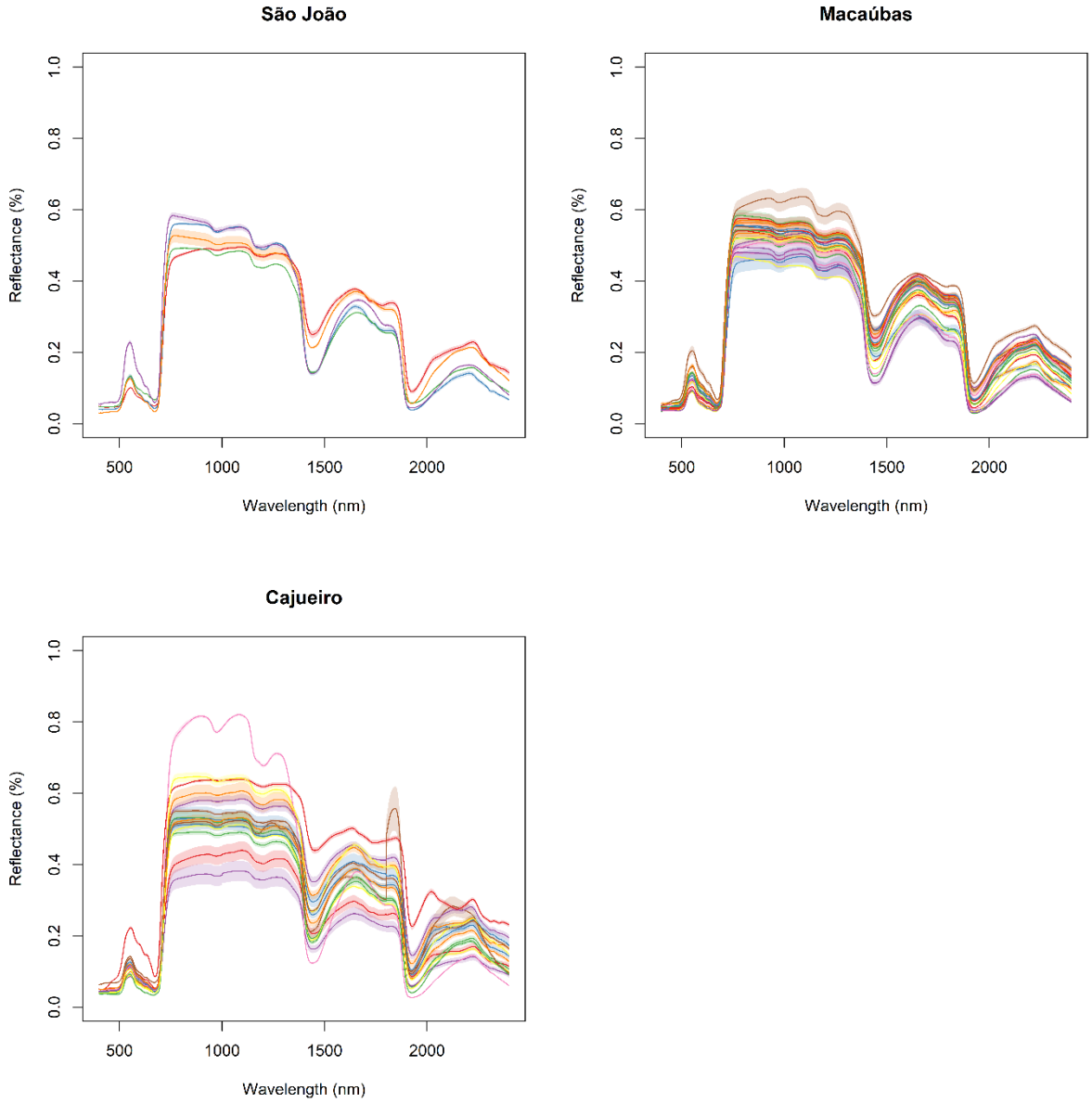


Figure 9. Mean reflectance (10 leaves) by species of Caatinga tree species collected across five sites: Petrolina - PE; Serra Talhada - PE; São João - PE; Macaúbas - BA and Cajueiro State Park at Matias Cardoso – MG. Each color are reflectance of tree species and the shadow area its standard error.

4. Other scientific activities

4.1 Internship abroad (Bolsa de Estágio de pesquisa no Exterior – BEPE)
Fapesp grant #2018/23845-0

Period of the internship: 1st February – 30th Abril 2019.

During this period I conducted an internship supervised by Prof. Anne Verhoef, at the University of Reading, UK. The main objectives in the original proposal for the internship were:

1) Analyze phenological data of 27 tree species to determine functional groups based on their leafing strategies and to identify their main environmental drivers for communities from three sites in Pernambuco state, Brazil. This objective was fully accomplished and to better describe its activities and results, I present a manuscript draft (see Item 3.3) and one abstract conference (Ramos et al. 2019; see Appendix I).

2) Collaboration with NORDEST Modelling working group towards the inclusion of the leaf phenology of plant functional groups in the modelling of carbon, water and energy fluxes of the Caatinga. Although this research is still in progress, this objective was fully accomplished and to better describe its activities and preliminary results, I present one abstract talk (Verhoef et al. 2019; see Appendix IV) and one abstract conference (Nóbrega et al. 2019; see Appendix III).

4.2 Papers published

*indicated papers not related to the present fellowship.

Moonlight et al., 2020. Expanding tropical forest monitoring into Dry Forests: The DRYFLOR protocol for permanent plots. Plant People Planet, 00:1-6. https://nph.onlinelibrary.wiley.com/doi/full/10.1002/ppp3.10112 Appendix V.

Paloschi, RA, **Ramos, DM**, Ventura, DJ, Souza, R, Souza, E., **Morellato**, LPC, Nobrega, RLB. Coutinho, IAC, Verhoef, A, Körting, TS, Borma, LS. 2021. Environmental Drivers of Water Use for Caatinga Woody Plant Species: Combining Remote Sensing Phenology and Sap Flow Measurements. Remote Sensing 13, 75. https://dx.doi.org/10.3390/rs13010075 (IF = 4.118) Appendix VI.

*__Ramos, DM__, Valls, JFM, Borghetti, F, Ooi, M. 2019. Fire cues trigger germination and stimulate seedling growth in grass species from Brazilian savannas. American Journal of Botany, 106:1190-1201. https://bsapubs.onlinelibrary.wiley.com/doi/full/10.1002/ajb2.1345

*Diniz, P, **Ramos, DM**, Webster, MS, Macedo, RH. 2121. Rufous horneros perceive and alter temporal coordination of duets during territorial interactions. Animal Behaviour. In press.

Observation: FAPESP is acknowledged in all publications above.

4.3 Conferences presentations

Talk with the main Post-doc results (Morellato & Ramos 2019; see Appendix II) at EGU General Assembly, in April at Vienna, Austria. The original title of the talk was "Tropical phenology and climate change in the 21st century: challenges and way forward" and Patricia Morellato was the speaker. However, due to her impossibilities to attend at the conference, I represented the Phenology laboratory. Link to the conference page: https://www.egu2019.eu/.

I also attended and present or co-authored presentations in two special sessions on "phenology and seasonality in climate change" and "hydrology, hydrogeology and soil-plant-atmosphere interactions in the Tropics", the last one related to dry forests ecology.

- **Ramos, D.M.**, Nóbrega, R., Verhoef, A., Moura, M.S.B., Souza, R., Souza, E.S., Lima, R., Lloyd, J., and **Morellato**, P. 2019. Leafing strategies of trees from Seasonally Dry Tropical Forests: the importance of rainfall variability. 2019. Poster presentation, Vol. 21, EGU2019-17863-2. (Appendix I).

- **Morellato**, L.P.C., and **Ramos, D.M**. 2019. Tropical phenology and climate change in the 21st century: challenges and way forward. Oral presentation. Vol. 21, EGU2019-18007. (Appendix II).

- Nóbrega, R., Moura, M.S.B., **Ramos, D.M.**, Santos, C.V.B., Miranda, R., **Morellato**, P., Lloyd, J., Prentice, I.C., and Verhoef, A. 2019. Ecosystem total LAI partitioning in a seasonally dry tropical forest. Poster presentation, Vol. 21, EGU2019-11881-1 (Appendix III).

- Verhoef, A., Nóbrega, R., Moura, M.S.B., Fatichi, S., **Ramos, D.M.**, Miatto, R., Majcher, B., Sabot, M., Souza, R., **Morellato**, P., Domingues, T., Prentice, C., and Lloyd, J. 2019. Using terrestrial ecosystem modelling to improve our understanding of drought survival strategies of a dry neotropical forest in Brazil (Caatinga). Oral presentation. Vol. 21, EGU2019-6049-2 (Appendix IV).

4.4 Participation in Committee Defenses, manuscript revisions and project proposals

I collaborate in the writing and submission of the project "Phenology of deciduous dry forest: a comparison at multiple spatial scales using phenocams and drones." This project was submitted to the FAPESP-FACEPE Edital 18/2018 and, then, latter to the

FAPESP Auxílio à Pesquisa – Regular. This project is a result of the successful collaboration between our phenology group from São Paulo and the local collaborators of the NORDESTE project in the northeast region of Brazil.

- Member of the committee of the under graduation defense of Victória Michaela Pires de Godoi "GERMINAÇÃO DE SEMENTES DO CERRADO: TEMPERATURA ÓTIMA, FORMA DE CRESCIMENTO, SÍNDROME DE DISPERSÃO E FENOLOGIA DE FRUTIFICAÇÃO", from the Ecologia course of UNESP, Rio Claro, SP.
- I participated as a member of the committee of the under graduation defense of Carolina de Abreu Crivelin "ANÁLISE DO EFEITO DE DIFERENTES ESCALAS ESPACIAIS NO ESTUDO DA FENOLOGIA VEGETATIVA REMOTA", from the Engenharia Ambiental course of UNESP, Rio Claro, SP.
- Member of the committee of the master defense qualification of Marco Chiminazzo "Atributos funcionais relacionados à regeneração pós-fogo", from the Biologia Vegetal course of UNESP, Rio Claro, SP.
- Member of the committee of the master defense qualification of Raquel Gasparini Martins "O EFEITO DA FUMAÇA NA GERMINAÇÃO E CRESCIMENTO DE PLÂNTULAS DE ESPÉCIES DO CERRADO", from the Biociências course of UNESP, Rio Claro, SP.
- Member of the committee of the master defense qualification of Rodolpho Luiz Barros de Medeiros "SENSORIAMENTO REMOTO DA FENOLOGIA DA CAATINGA E SEUS DRIVERS AMBIENTAIS", from the Meteorologia course of UFCG, Campinas, PB.
- I revised five manuscripts, for Plant Biology journal, Flora Jena journal, Plant Ecology journal, American Journal of Botany journal and Seed Science Research journal.

5. Use of Research Contingency Funds (Reserva Técnica)

The research contingency funds were used mostly to cover the costs of flight tickets, hotel and meals for all the field works necessary to set up the Phenocam Network, totaling 18 cameras at seven sites at northeast region of Brazil. I also have used the RT to cover the costs of lithium batteries, memory cards, supports for set up and other materials necessary

to maintain the Bushnell cameras turned on continuously in these sites. It was also necessary to buy six external hard drives to store images from the all the seven sites. The detailed description of all expenses is in SAGe system, as requested by Fapesp.

6. Institutional support

During my research period I received all the support necessary to conduct my research at the Laboratory of Phenology from the Departamento de Biodiversidade da UNESP, campus Rio Claro. These includes all the facilities of my installation in an office, furniture, phone, printer and mail services to send material to the collaborators in the sites at northeast. I had the full support of my supervisor from Brazil and co-Pi of NORDESTE Project, Prof. Patricia Morellato, and her team to learn all the skills and acquire the necessary knowledge to be able to start the camera set up for the NORDESTE network. I have also received continuous support to learn the processing steps and develop the analyses, mostly using the tools developed by the e-phenology team and Phenology Lab. I had regular meetings with my adviser and, based on that, we planned the phenocam network and my activities, outline the first paper draft present in this report and planned the collaboration with other groups within Nordeste project, discussed all activities, the results and manuscripts outline and writing. I have also received the necessary support from the Coordinator of the NORDESTE project, Prof. Jon Lloyd, and the co-PI Dr Tomas Domingues for all activities in the field. During the BEPE period with Prof. Anne Verhoef I received the institutional support from the Department of Geography and Environmental Science School of Archaeology, Geography and Environmental Science from University of Reading, UK.

7. Supervisor evaluation and justification for the Post-doc extension

Dr Desiree Marcos Ramos has been and exceptional pos-doctoral fellow. Although she has started with no previous experience on near-remote phenology and phenocameras or with FAPESP funding projects, now has acquired all necessary skills and competence as a research in the area of near-remote phenology, ecology and dynamics of seasonally dry tropical vegetations. The set up the Nordeste phenocam Network was time-consuming but the first results and future prospects are remarkable and leaves no doubts on the high-quality productivity in the upcoming year. Desiree also received advise from me on the prospects of integrating phenology to other Nordeste project work groups, and

that has fruitful results, some already published and ongoing research articles. I again stress that Desiree performed an enormous amount of field work, that would be a challenge for any strong field ecologist. She worked at Nordeste long field campaigns, set up all cameras and collaborated, as requested by Dr Lloyd, in the set up of Nordeste plant plots and plant collections (WP1) and collaborated with Dr Domingues and Dr. Miatto on WP5.

Therefore, advised and planned for her activities, Desirée performed the integration with physiology and trait-based teams for the better understanding of phenological leaf strategies according to functional groups and physiological responses, building an integrated evaluation of Caatinga responses to dry conditions. In addition to that, Desiree was trained in the Phenology Lab and acquired leaf spectral traits of Nordeste species, to be associated with the other functional traits collected according to the protocols of Nordeste project.

Over the last year Desiree processed an enormous amount of images, extracted the greening indexes, interpreted results and performed key analyses in the Phenology Lab and during her stay in Reeding during her BEPE and paved the strong collaboration with Dr Veenhof team towards modeling the Caatinga. Desirée is an excellent companion and great person to have around, in the field or Lab, easy to work with, reliable and participating of all activities, proactive and always ready to support her colleagues and collaborate. I strongly support her application for the final extension of her fellowship, if the Nordeste Project receive a final extension.

That final extension would be essential to identify the species of the two remaining sites and finalize at least there more manuscript as first author, besides at least two more as a collaborative research with WP5 and WP7.

The collaboration we have initiated with other research groups is again an important point to consider in the decision of applying for the Post-doc project extension. We are providing data that has been integrated in the modelling of water, energy and carbon balance of the Caatinga biome, and in the study of physiology and sap flow of Caatinga tree species (see recent paper Paloschi et al. 2021). We argue that the extension of the Post-doc project will allow the conclusion of several papers from these collaborations and three papers lead by the pos-doc Desiree Ramos, besides those in collaboration with other WGs (See Moonlight et al. 2020). We have done a huge field effort to set up all of the Nordeste Phenocam Network and just now we have a full set of data with at least one complete growth season processed and analysed.

Finally, we remind FAPESP board and referees that Desiree was in a pregnancy leaving during four months. And we have the pandemic, hampering our ability to finish field work and slowing down the analysis and writing. Even considering all this scenario, Desiree performance was outstanding.

8. Work plan for the Post-doc extension period (5 months)

Climate drivers and eco-physiological constraints of leaf phenological patterns of seasonally dry forests

8.1 Objectives

1) Finish the writing and submission of the three manuscripts proposed in items 3.3 to 3.5.
2) To keep the work of maintenance and functioning of the Nordeste Phenocam Network.
3) Finish at least four more collaborative research with WP5 and WP7.

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8. Appendices

Appendix I

Geophysical Research Abstracts
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Leafing strategies of trees from Seasonally Dry Tropical Forests: the importance of rainfall variability

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The Caatinga biome constitutes the largest area of Seasonally Dry Tropical Forest (SDTF) in the New World, covering an area of ca. 850,000 km² located in North-eastern Brazil. The climate in Caatinga is semi-arid with annual precipitation ranging from 250 to 1200 mm, and the dry season can range from five to nine months in duration. Harsh conditions constrain species' leafing patterns in the Caatinga and, consequently, most species are deciduous, losing their leaves during the dry season and flushing in the rainy season. Another important characteristic of the Caatinga is that the interannual variability of precipitation increases along a gradient of aridity (Petrolina – 387 mm; Serra Talhada – 574 mm and São João – 800 mm; see Souza et al., 2016). Considering the strong seasonality and aridity of Caatinga, and the phenological adaptations of tree species to drought mentioned above, we aim to address the following questions: 1) What are the dominant leafing patterns and their main climatic drivers? We use the near-surface remote phenology method from digital cameras (Alberton et al., 2017) to track the leaf flush and fall in Caatinga arboreal vegetation, during one growing season from 2017 to 2018, and its relationships to climatic conditions (daily precipitation, temperature and photoperiod); 2) Are leafing patterns and leaf exchange strategies influenced by rainfall variability in a gradient of aridity across sites? We compare the species' promptness to flushing (*i.e.* the lag time for plant response after first rains) and deciduousness across a gradient of aridity in Petrolina, Serra Talhada and São João municipalities. Supported by FAPESP-NERC (FAPESP #2015/50488-5).

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Appendix II

Geophysical Research Abstracts
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Tropical phenology and climate change in the 21st century: challenges and way forward
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Tropical phenology is a complex issue as much as the study of tropical diversity. Temporal changes on plant responses to climate are hard to track on tropical systems from individual plants, species to ecosystems. Recently, new technology and computational tools have allowed a better understanding of tropical phenology and its responses to environmental cues. However, we still lack a thoughtful comprehension of drivers and clues for flowering, fruiting or leaf exchanging patterns in tropical ecosystems. Here we explore from traditional (e.g. direct observation, plant traps, land surface phenology) to innovative approaches (e.g. phenocameras, herbarium record, phylogeny, distribution and ecosystem modeling) on plant phenology and discuss the way forward to achieve a consistent progress in our knowledge of tropical plant phenology and their responses to climate change.

Appendix III

Geophysical Research Abstracts
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Ecosystem total LAI partitioning in a seasonally dry tropical forest

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The leaf area index (LAI) is a measure of the one-sided leaf area per unit ground area; it is a crucial parameter used in different environmental modelling frameworks, such as climate-, soil-plant atmosphere-, and hydrological models. LAI has been quantified for different vegetation types around the world by using methods that are usually non-destructive, and based on remote sensing and indirect field measurements (e.g. via measuring light extinction). Although these methods are useful for estimation of ecosystem total LAI (hereafter referred to as total LAI), there is a lack of studies that partition the total LAI into LAI for individual plant species within the ecosystem. This is particularly important for biodiverse (semi-) natural ecosystems, but also has value in an agroforestry or intercropping context. Here, we present an effort to estimate LAI for specific species of the Caatinga biome, a seasonally dry forest in the semi-arid northeast of Brazil, with 30–60 plant species per ha. The trees and shrubs of the Caatinga have a strong seasonal and inter-annual variation in phenology, which causes LAI to vary widely. The vegetation reaches a LAI of 4 m2 m-2 during the wet season (despite the low ratio (~0.2) of precipitation over potential evaporation), and most of the species become leafless for periods ranging from weeks to months during the dry season. In this study, we partitioned the total LAI for a caatinga site located in Petrolina, Pernambuco state. We used a total LAI daily time series from 2011 to 2017 and the coverage fraction of each species as primary data to apply criteria to obtain the LAI for individual plant species. First, we collected species-based field LAI measurements to establish the relation of LAI between species during the wet and dry seasons. We then obtained data from a phenological camera to assess how the leaf growth and senescence differ between the species in response to soil moisture variations. We considered these analyses to develop a LAI partitioning algorithm for this caatinga vegetation. Our results show that species that are dominant in terms of coverage fraction have a determining role in the ecosystem LAI, but that this can also mask low or peak values in LAI of species that possess low coverage fraction. This finding has essential ecosystem implications because plant species have different traits (such as maximum carboxylation velocity and maximum rate of photosynthetic electron transport), which will, together with the LAI, quantify the water and carbon fluxes of an ecosystem. Our study supports the development of model approaches for the Caatinga biome by overcoming the limitations of

using total LAI values, which allows the discretization of LAI time series for different species in terrestrial Caatinga ecosystem models.

Appendix IV

Geophysical Research Abstracts
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Using terrestrial ecosystem modelling to improve our understanding of drought survival strategies of a dry neotropical forest in Brazil (Caatinga)

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The Caatinga is a deciduous seasonally dry neotropical forest, which is the dominant vegetation type in the northeastern region of Brazil. It covers an area of ca. 850,000 km2 and it consists of over 1,000 vascular plant species, characterized by different biophysical and physiological traits and drought survival strategies, adapted to its semiarid climate. In recent years, this area has endured a number of prolonged droughts that have adversely affected this already severely water-limited region. Our research focus is on increasing the understanding of the functioning of this complex ecosystem, by developing and employing terrestrial ecosystem models; this is fundamental for the design of suitable conservation strategies. We conducted a detailed multi-model study using driving and verification data (from 2011 onwards) for a pristine Caatinga 'Fluxnet' site, near Petrolina, Brazil. Data collected included eddy covariance measurements of whole ecosystem carbon, water and energy fluxes, as well as measurements of leaf area index, phenology, surface temperature and soil moisture content. The models comprised the ecohydrological model Tethys-Chloris (Fatichi et al., 2012), that has already been successfully employed for the simulation of savannah, cerrado and tropical rainforest ecosystems, as well as two other more recently developed models. One of these concerns a bespoke Caatinga terrestrial ecosystem model, CaaTEM, broadly based on the model equations described in Verhoef and Allen (2000) and Wallace and Verhoef (2000). This model estimates the light interception, fluxes of energy and photosynthesis, and surface temperature of the individual components of a multi-species mixture, such as the Caatinga ecosystem. The third model involves a framework that optimizes carbon uptake whilst maintaining hydraulic function, currently being developed at the University of New South Wales, Australia. With

these models, we investigated the intricate interactions between Caatinga species with regards to competition for light (above-ground) and water (below-ground), as well as the role of phenology in the seasonal and inter-annual evolution of land surface-atmosphere exchanges. Emphasis was on assessing the relative influence of aerodynamic (as affected by above-ground canopy architecture, phenology and leaf dimensional properties) and surface resistances (determined by the species' physiological and hydraulic plant traits) on energy, water and carbon transfer.

This work has been supported by FAPESP-NERC (FAPESP #2015/50488-5).

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Appendix V

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Plants People Planet PPP Open Access

BRIEF REPORT

Expanding tropical forest monitoring into Dry Forests: The DRYFLOR protocol for permanent plots

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Appendix VI

remote sensing

MDPI

Article

Environmental Drivers of Water Use for Caatinga Woody Plant Species: Combining Remote Sensing Phenology and Sap Flow Measurements

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Abstract: We investigated the water use of Caatinga vegetation, the largest seasonally dry forest in South America. We identified and analysed the environmental phenological drivers in woody species and their relationship with transpiration. To monitor the phenological evolution, we used remote sensing indices at different spatial and temporal scales: normalized difference vegetation index (NDVI), soil adjusted vegetation index (SAVI), and green chromatic coordinate (GCC). To represent the phenology, we used the GCC extracted from in-situ automated digital camera images; indices calculated based on sensors included NDVI, SAVI and GCC from Sentinel-2A and B satellites images, and NDVI products MYD13Q1 and MOD13Q1 from a moderate-resolution imaging spectroradiometer (MODIS). Environmental drivers included continuously monitored rainfall, air temperature, soil moisture, net radiation, and vapour pressure deficit. To monitor soil water status and vegetation water use, we installed soil moisture sensors along three soil profiles and sap flow sensors for five plant species. Our study demonstrated that the near-surface GCC data played an important role in permitting individual monitoring of species, whereas the species' sap flow data correlated better with NDVI, SAVI, and GCC than with species' near-surface GCC. The wood density appeared to affect the transpiration cessation times in the dry season, given that species with the lowest wood density reach negligible values of transpiration earlier in the season than those with high woody density. Our results show that soil water availability was the main limiting factor for transpiration during more than 80% of the year, and that both the phenological response and water use are directly related to water availability when relative saturation of the soil profile fell below 0.25.

Keywords: plant water availability; tree phenology; phenocams; Sentinel-2; MODIS

1. Introduction

A better understanding of plant water availability and water use is of great importance for reliable assessments of ecosystem's resilience to droughts [1]. Water availability is critical for plant growth, inducing phenological transitions and, ultimately, plant survival.

Appendix VII
Manuscript draft

Leafing strategies of trees from Seasonally Dry Tropical Forests: the importance of rainfall variability

Abstract

Leaf exchanges of trees from seasonally dry tropical forests (SDTFs) are triggered by the environmental cues precipitation, temperature and photoperiod, but also determined by stem water status, which in turn is influenced by wood density. Caatinga vegetation, located in Northeastern Brazil, is a SDTF where the environmental conditions and species diversity can be highly variable across areas. Thus, we asked: 1) Do the leafing patterns and leaf exchange strategies differ according to the rainfall variability across the gradient of aridity? Are the responses related to the species woody density? 2) What are the main climatic drivers of leaf exchange and deciduousness of Caatinga vegetation? We studied the leaf phenological patterns of 126 individuals of 22 tree species in a gradient of rainfall across three sites (Petrolina, 340 mm; Serra Talhada, 620 mm and São João, 770 mm), and during two growing seasons. We use the near-surface remote phenology method from digital cameras with fine temporal daily resolution to track the leaf flush and fall in Caatinga woody vegetation and related to local weather conditions (daily precipitation, soil moisture, temperature, photoperiod and vapour pressure deficit) and the tree species wood density. We found that all species of the three sites were deciduous. The leaf flushing was synchronic among species during the beginning of the rainy season in PET and STA, but not in SJO. Leaf fall, on the other hand, was not synchronic, showing high variability among species for the three sites. The species' length of growing season (LOS) tended to increase towards the increase of rainfall from PET and STA to SJO. Leaf flushing nor leaf fall was related to species' wood density in the three sites. Soil moisture was the main climatic driver triggering the leaf flushing and fall for Caatinga tree species from the three sites regardless of their wood density. Our findings indicate that aridity constrains the species' phenological patterns with soil moisture being the main environmental driver to the leaf exchanges of Caatinga vegetation.

Key-words: Caatinga; environmental drivers; leaf phenology; phenocam; SDTF.

Introduction

Seasonally dry tropical forests (SDTFs) cover about 42% of the world's forested area (Murphy & Lugo 1986), with more than half (54.2%) located within South America (Miles et al. 2006). The climate in SDTFs is characterized by both the low amount and high seasonality of rainfall that is often exceeded by potential evapotranspiration, with characteristic prolonged dry seasons (Murphy & Lugo 1986; Quesada et al. 2009). The vegetation within neotropical SDTFs varies from scrub to tall trees, in regions with an average rainfall ranging from 250 to 2,000 mm/year (Murphy & Lugo, 1986; Pennington et al. 2009). The scarcity of rainfall and prolonged dry season together determine harsh conditions for leaf functioning. Under these circumstances, plants in SDTFs have developed drought survival strategies that include decidual leaf phenology during the dry season and synchronic leaf flushing during the rainy season (Borchert 1994; Lima et al. 2012; Alberton et al. 2019).

The environmental cues triggering leaf exchange in trees from seasonally dry ecosystems are predominantly precipitation, temperature, and photoperiod (Wright & van Schaik 1994; Camargo et al. 2018; Alberton et al. 2019). Along a gradient of increasing rainfall seasonality, the most important drivers for leaf exchange shifts from photoperiod to cumulative water deficit (CWD), as observed for the Brazilian savannas (Cerrado), and SDTFs (Caatinga), respectively (Alberton et al. 2019). However, where aridity is strong, such as in the SDTFs, the deciduousness tree strategy is not determined only by environmental inputs (*e.g*., precipitation) but by the interaction between seasonal precipitation and stem water status (Borchert 1994; Lima & Rodal 2010; Lima et al. 2012; de Oliveira et al. 2015), which in turn is influenced by wood density and root depth (Borchert 1994; Lima et al. 2012). Trees can be divided into two classes based upon wood density: deciduous with high wood density (DHWD) and deciduous with low wood density (DLWD), with low and high stem water storage capacity, respectively (Borchert 1994; Lima et al. 2012). Species can therefore be classified into functional types according to the deciduousness strategy (leaf out or deciduousness strategy) as well as by their wood density (Borchert 1994; Lima et al. 2012; de Oliveira et al. 2015), improving our capability to investigate the plant response to seasonally dry, stressful environments.

The Caatinga domain constitutes the largest area of SDTF in the New World, located mostly in Northeastern Brazil (Araújo et al. 2007; de Queiroz et al. 2017). A variety of vegetation types can be found in the Caatinga, from scrublands to forests, encompassing rich to poor nutrient soils types, across a semi-arid climate (Köppen's BSh; 1931; Särkinen et al. 2011). Caatinga biome total annual precipitation ranges from 250 to 1200 mm, and the dry season can range from five to nine months in duration (Araújo et al. 2007; de Queiroz et al. 2017). Harsh conditions constrain species' leafing patterns in the Caatinga and, consequently, most species are deciduous, losing all theirs leaves during the dry season and flushing in the rainy season (Barbosa et al. 1989; Amorim et al. 2009; Lima et al. 2012; Pezzini et al. 2014; de Oliveira et al. 2015).

The interannual variability of precipitation increases along a gradient of aridity in different areas of the Caatinga vegetation (Souza et al. 2016). Interestingly, in more arid areas the community is composed by deciduous species that often flush immediately in a synchronized response to small pulses of precipitation (Alberton et al. 2019), while in less arid areas it is possible to find a greater diversity in phenological strategies such as evergreen, short and long deciduous species (Amorim et al. 2009; Lima et al. 2012; de Oliveira et al. 2015). The two functional groups of deciduous trees DLWD and DHWD from the less arid areas have different leaf flush and fall patterns driven by different climatic factors (Lima et al. 2012; de Oliveira et al. 2015). The leaf flush and fall occur earlier for the DLWD than for the DHWD species, driven by photoperiod and precipitation, respectively (Lima et al. 2012).

Phenological data have been successfully used to understand ecology from the individual level, as in plant-animal interactions, to the ecosystem level, in terms of the role of vegetation dynamics in driving carbon and energy fluxes (Migliavacca et al. 2011; Morellato et al. 2016; Alberton et al. 2019). This newly realized potential of phenology as a monitoring tool in tandem with recent advances in technology has stimulated the use of novel phenology monitoring techniques such as the repeated photographs. The Green Chromatic Coordinate (Gcc) greenness index (Richardson et al. 2018) extracted from daily sequence of digital images is a reliable measurement of leaf flushing in seasonal

tropical ecosystems (Alberton et al. 2017; Alberton et al. 2019). Therefore, digital cameras collect finely resolution daily phenological data of several individuals and plant species, simultaneously at different sites, essential to evaluate the environmental triggers of leafing in seasonal ecosystems (Alberton et al. 2017; Richardson et al. 2018). This is particularly important for studying phenology of the Caatinga vegetation, since plants can flush synchronously few days after low rainfall events (Machado et al. 1997; Amorim et al. 2009; Lima & Rodal 2010; Alberton et al. 2019), making it difficult to accurately register the leaf flush with the low frequency observations of traditional on the ground phenology methods.

Considering the strong seasonality and aridity of Caatinga, and the phenological adaptations of tree species to drought in SDTF mentioned above, we aim to describe the dominant leafing patterns of Caatinga tree species across three sites that represent a gradient of rainfall (375–765 mm year). Specifically, we address the following questions: 1) Do the leafing patterns and leaf exchange strategies differ according to the rainfall variability across the gradient of aridity? Are the responses related to the species woody density? We use the near-surface remote phenology method from digital cameras to track the leaf flush and fall in Caatinga woody vegetation and relate to local weather conditions (daily precipitation, soil moisture, temperature, photoperiod and vapour pressure deficit) and the tree species wood density; 2) What are the main climatic drivers of leaf exchange and deciduousness?

Methods

Study area

The study was conducted in a large area of Caatinga vegetation in Pernambuco State, Northeastern Brazil, at three sites under contrasting precipitation patterns: Petrolina (PET), Serra Talhada (STA) and São João (SJO) (Fig. 1A). During our study, the three sites were equipped with flux towers and phenocams for phenological monitoring (details in subsection *Camera set up and images processing*). The climate is predominantly semi-arid climate (Köppen's BSh) with a gradient of aridity across the study sites. We used long-term rainfall data available for the three sites provided by the Agência Pernambucana de Águas e Clima – APAC, which corresponds to the periods of 1991–2019 (for PET and

STA) and 2000–2019 (for SJO). The code of the APAC stations used for these calculations are 4, 12, 13, 61, 160, 165, 171, 229, 239, 240, 281, 313, 538, 539. The aridity index, i.e. ratio between rainfall and potential evapotranspiration, and the mean total annual rainfall precipitation are approximately 0.19 and 340 mm for PET, 0.28 and 620 mm for STA and 0.47 and 770 mm for SJO (Souza et al., 2016). The months with average rainfall above the historical mean are November–April (91% of total annual rainfall) in PET, January–May (78% of total annual rainfall) in STA, and May–August (57% of total annual rainfall) in SJO (Fig. 1B).

The first and driest site, PET, is a protected area from the Brazilian Agricultural Research Corporation (Embrapa, Semiarid unit), located at Petrolina municipality (9.0480° S, 40.3198° W) at 395 m a.s.l. The area has been protected from grazing and anthropic disturbs during the last 40 years. The most common soil is Acrisol and the vegetation is a scrubland composed of trees with average height of ~4.5 m and tree density of approximately 500 individuals/ha, according to the data from the RAINFOR Permanent Plot Network, collected during the inventory of project NERC-Newton-FAPESP *Nordeste: New Science for A Neglected Biome* (#NE/N01247X/1; #NE/N012550/1; #2015/50488-5; for details on the *Nordeste* project, see Moonlight et al., 2020). The dominant tree species are, in this order, *Senegalia polyphylla*, *Manihot* sp., *Cenostigma microphyllum*, *Sapium glandulusom Handroanthus spongiosus* and *Commiphora leptophloeos,* with a shrubby stratum dominated by the bromeliad *Neoglaziovia variegata* (Miranda et al., 2020).

The second site, STA, is an experimental area located at Serra Talhada municipality (7.97008° S; 38.3849° W) at 467 m a.s.l. The area is grazed by cattle and goats during the rainy season. The main class of soil is Calcisol and the vegetation is mainly composed of trees with average height of ~5 m and tree density of approximately 780 individuals/ha (*Nordeste* project). The dominant tree species are, in this order, *Aspidosperma pyrifolium*, *Cenostigma nordestinum, Senegalia polyphylla* and *Anadenanthera colubrina* var*. cebil*.

The third and wettest site, SJO, is a relatively small experimental area surrounded by agricultural lands located at São João municipality (8.80967°S; 36.4054°W), at 762 m a.s.l. The area is

grazed by cattle and goats during the entire year. The most common soil is Arenosol and the vegetation is mainly composed of trees with average height of ~5 m and tree density of approximately 670 individuals/ha (*Nordeste* project). The dominant tree species are, in this order, *Pilosocereus pachycladus*, *Commiphora leptophloeos*, *Mimosa tenuiflora*, *Piptadenia flava*, *Lippia origanoides* and *Sapium glandulosum*.

The rainfall intra- and inter-annual temporal and spatial variability in this region is particularly high with standard deviations that are often greater than the historical mean (Fig. 1B), therefore shifts of 1 to 3 months in the wet seasons onset are expected. For example, the rainfall during March and April in SJO is below but still very close to the historical mean, and these months exhibit relatively high standard deviations (68.1 and 39.7 mm, respectively); therefore, they may be part of the wet season depending on the period analyzed. In 2018, the annual rainfall was greater (446 mm in PET), similar (646 mm in STA) and below (555 mm in SJO) the historical mean; and the wet seasons were shorter in PET (January–April) and STA (February–April), and substantially early in SJO (February–May). In 2019, the annual rainfall was 5–20% lower than the historical mean in all three sites with 277 mm in PET, 554 mm in STA, and 730 mm in SJO. In that year, there was a small shift of the wet season in PET (February–May) and STA (January–April), and a wet season within the historical boundaries in SJO (June–August). Still, PET and SJO sites exhibited a month with rainfall higher than the historical mean but also out of the wet season period. In PET, the rainfall in December of 2019 of 46 mm was succeeded by no rainfall in January 2020. In SJO, March of 2019 was the wettest month with 184 mm (25% of the total annual rainfall), but the wet season only started in June.

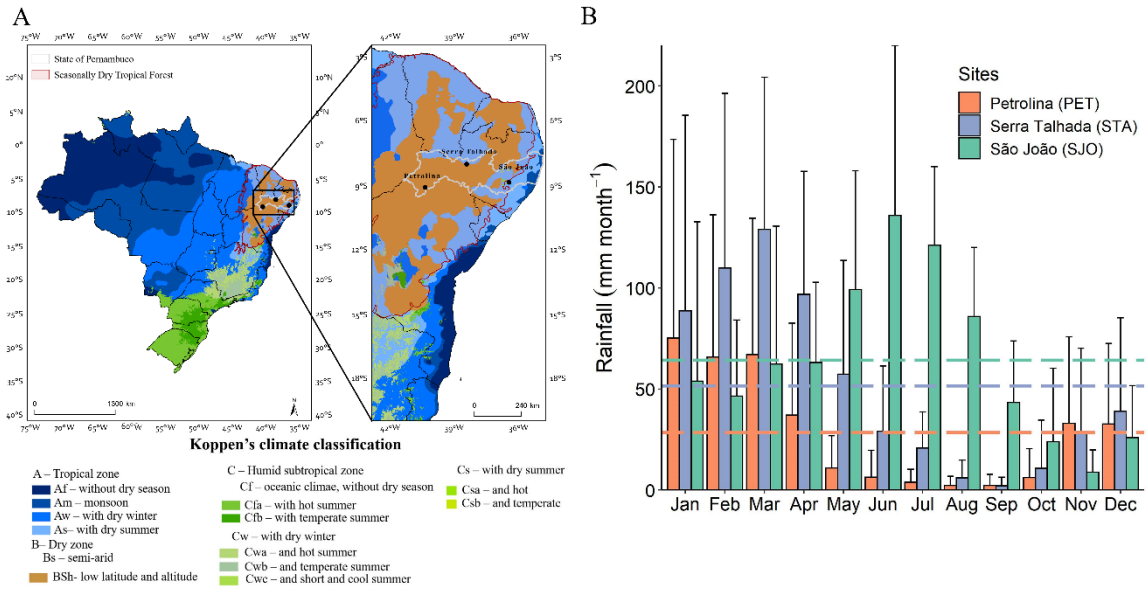


Fig. 1. Location and climate of Caatinga SDTF (A) delimited by the red line, in Brazil; in the detail the Pernambuco State (withe line) and the study sites (black dots). Koppen's climate classification for Brazil from Alvares et al. (2013) with emphasis for the semi-arid climate of Caatinga SDTF; (B) Total monthly rainfall of Petrolina (PET), Serra Talhada (STA) and São João (SJO) sites. The bars are rainfall monthly means with lines showing their respective standard deviation values, and the dashed lines are monthly annual means (2000–2019) for each site. Details for the weather station in the Methods.

Climatic and environmental variables

The climatic data from each site were recorded during the corresponding period of the phenology monitoring, by the respective flux towers sensors where the phenocameras were set up. The relative humidity, maximum, minimum and average air temperatures were measured with a HMP45C instrument (Vaisala, Campbell Scientific Inc., Logan, UT, USA). Total daily rainfall was measured with a tipping-bucket rain gauge (model TE 525 WS-L, Texas Electronics, Dallas, TX, USA). Soil moisture at 20 cm depth was measured with Campbell scientific TDR sensor (model CS616). We choose the 20 cm depth because most of the total biomass of coarse roots of trees in the Brazilian dry forest are in the upper 20 cm of the soil profile (Costa et al. 2014). We used the number of sunlight hours as a measure of the day length, calculated with the Geosphere R package (*v. 1.5-10*; Hijmans, 2019) for the latitude of each site.

In plants, water fluxes are primarily driven by a water potential difference between the leaf and soil. At the leaf level, the transpiration rate is mainly regulated by a combined response of the stomata to atmospheric evaporative demand, i.e. vapour pressure deficit (VPD), photosynthetically active radiation (PAR) and wind (Meinzer et al. 2001). So, VPD is considered an important driver for transpiration in plants (Amitrano et al. 2019) and is quantified as the difference between the saturation vapour pressure and the vapour pressure at a given temperature. The VPD increases as the temperature increases and relative humidity decreases, and even though that a certain level of VPD is necessary for water absorption, high values of VPD can be stressful for leaves. In our study, we evaluate the VPD as a driver of leafing patterns at a daily scale, using the relative air humidity and temperature to calculate it according to (http://cronklab.wikidot.com/calculation-of-vapour-pressure-deficit).

To measure wood density, we followed (Pérez-arguindeguy et al. 2013). We cut one branch of approximately 10 cm length, avoiding bifurcations and tortuous sections. After rehydration, we removed the outer bark and obtained the volume of the branch by using the dimensional method: we took the diameter at two points in each tip of the branch with a digital caliper and measured the exact branch length with the same caliper. With average diameter and the length, we calculated the cylinder volume as: pi x R^2 x length. Then, we oven-dried the branch at 80 °C for at least 48 h and weighed the dry mass on an analytical scale. We divided the oven-dried mass by volume to obtain the wood specific density. Even though the protocol suggests temperature closer to 100°C due to the bound water content, we had to keep the temperature lower as we were also drying leaves concomitantly. We averaged the wood density by individuals of the same species to calculate the mean wood density by species. When the same species was collected in more than one site, we first calculated an average for the individuals of the same species inside the same site, then calculated the average for the species across sites. Finally, to categorize species in strategies of wood density, we divided them as having low (<0.50) and high (>0.50) wood specific density (Borchert 1994; Lima et al. 2012). The number of individuals used to calculate wood density varied among species and sites (see supplementary material SI for sample sizes).

Camera set up and images processing

One digital hemispherical lens camera Mobotix Q 25 (Mobotix AG — Germany) was set up at each site in November 2017, before the beginning of the growing season, at the top of the flux tower surrounded by native vegetation and angled downward (180°), providing a hemispherical view of the trees' canopies following e-phenology protocol (Alberton et al. 2017) (Fig. 2). The leafing patterns were registered during two growing seasons from 2017 to 2019, with slightly different starting dates for each site: Petrolina (PET): 01/11/2017 to 31/12/2019, Serra Talhada (STA): 28/11/2017 to 27/08/2019 and São João (SJO): from 19/12/2018 to 31/12/2019. The cameras were set up facing northeast, 7 to 10 m above the vegetation canopy. Three to five JPEG images (at 1280x960 pixels of resolution) were automatically taken hourly, in the first minute of each hour, from 06:00 to 18:00 h (UTC−3; Universal Time Coordinated). The camera was connected to an energy supply system composed by a 12V battery which was charged by solar panels attached to the tower. At each site, the images, the trees' crowns were delimited as a region of interest (ROI) for the following analysis (Alberton et al. 2014): the individuals of each species were identified from the tower and their crowns drawn in the images (Fig. 2), then their identification confirmed on the ground. The number of species and individuals identified in the images and used for the phenological indices varied between sites (Table 1; see supplementary material SII for phenological sample sizes). We also delimited one community ROI for each site, which consisted in the whole vegetation image and excluding the tower.

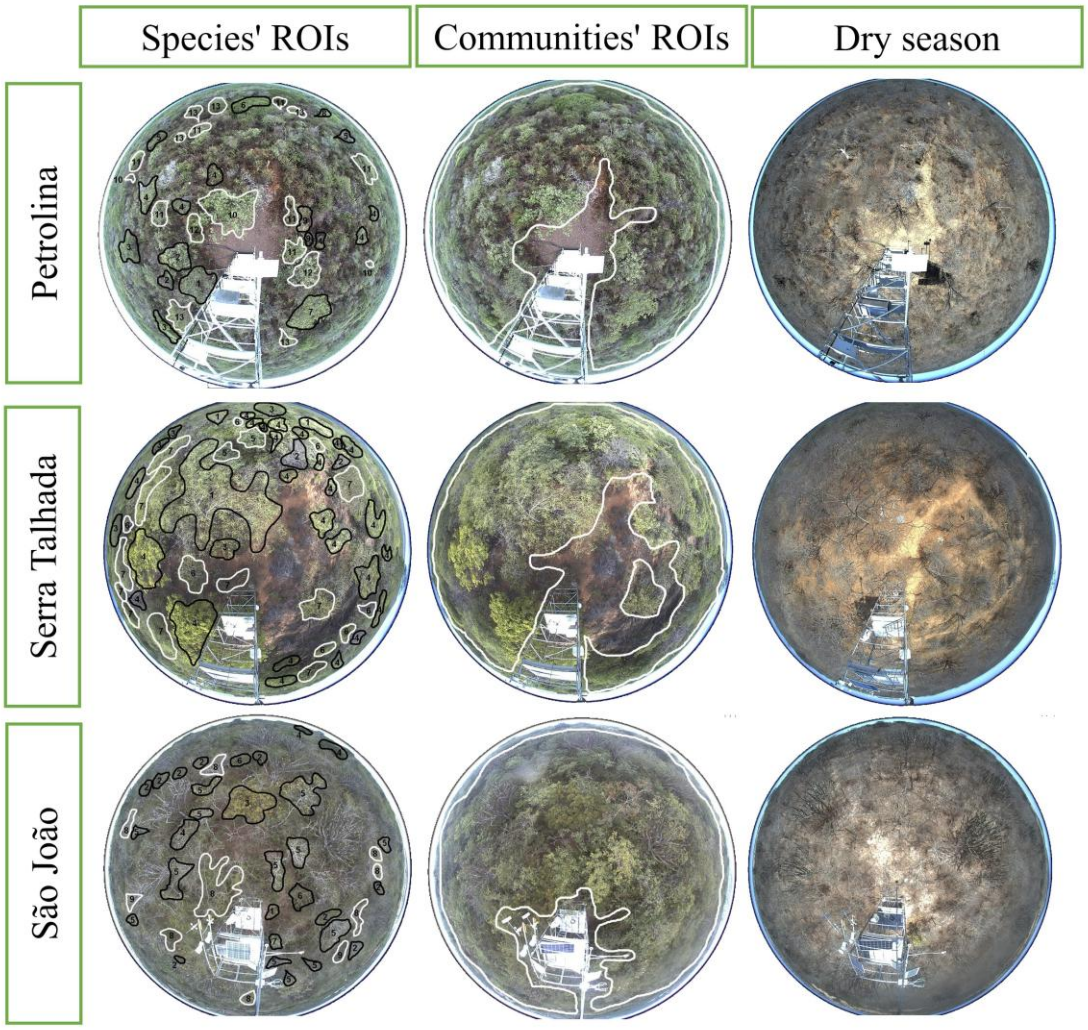


Fig. 2. Field of view for the Mobotix cameras from Petrolina, Serra Talhada and São João study sites with their Regions of interest (ROIs) drawn at species and community levels. The black and white ROI colors represent tree crowns of individuals from species with high and low wood density, respectively. The images in the last column are from the dry season while the communities' ROIs image represents the rainy season.

Data analyses

Camera near-remote phenological index

We previously made a visual inspection to exclude images not suitable for the index extraction, such as dark images or with too much sunlight exposure. Then, the digital numbers (DNs) red, green and blue color channels (RGB) were extracted from the JPEG images for each ROIs across the images on a given day. The index Green Chromatic Coordinate (Gcc; Alberton et al. 2017; Richardson et al.

2018), which is a measure of canopy greenness, was extracted. This involves calculating the ratio of the relative brightness of the green color channel (green DN) over the total DN brightness: Gcc = green DN/ (red DN + green DN + blue DN). Changes in Gcc values are a reliable measurement of the changes in the leaf flushing patterns (Alberton et al. 2017). To reduce the noise in the Gcc patterns caused by seasonal or time of the day illumination effects, we used the 90th percentile calculated from all daily values (Sonnentag et al. 2012).

Phenological metrics

We calculated, for each individual, the date of start (SOS), end (EOS) and length (LOS) of growing season following Alberton et al. (2019). First, we fitted a generalized additive model (GAM) using the Gcc as the response variable fitted by time, (i.e. the sequence of consecutive days of the phenological observations) to produce the phenological curves. Second, we calculate which regions of the curve have derivatives, performing, in the sequence, 10000 simulations to calculate the confidence intervals (95%) to detect where these derivatives are significantly different from zero (Alberton et al. 2019). Third, we detected where the derivatives were increasing (start of growing season SOS) or decreasing (end of growing season EOS). Finally, we visually verified in the images, in the period corresponding to the increasing and decreasing derivatives, when the first leaves were produced (greenness rising date) and when the leaves were totally dropped (greenness falling date). We considered the length of growing season as the difference between SOS and EOS dates (Alberton et al. 2019). We calculated the mean length of growing season for the species of each site by averaging the length of growing season for each individual, when they had more than one period of leaves inside the same rainy season, then for all individuals of the same species.

Statistical analysis

To compare if the start and end of growing season differed among species from low and high wood density functional groups, we used the date (day and month) of the first individual to flush as starting point (value 1) and counted how many days the other individuals took to flush and to drop their leaves after this starting point. We considered the same starting point for both growing seasons,

for example, the starting point was 5th November for Petrolina and the individuals' SOS/EOS were counted after this date but relatively to each growing season. This approach resulted in a continuum value of the start of growing season instead of a date for each individual from each species. Then, we fitted a Generalized Linear Mixed Model (Brooks et al. 2017) using the SOS and EOS, separately, as the response variables and the wood density groups plus the growing season as fixed factors. We also included the species, nested as random effects to control for their variation in the model. We performed this analysis for each site, separately. We used the glmmTMB package from R software (Brooks et al. 2017) for this analysis.

We tested for the influence of environmental and climatic variables in the phenological patterns (*i.e.* changes in Gcc), for each site, separately. We analyzed Gcc as the response variable and the daily average temperature, day length (photoperiod), accumulated daily rainfall, VPD and daily soil moisture as predictors. Because the relation of phenology and the environmental and climatic variables is usually not linear, we fitted Generalised Additive Models (GAM; see Wood 2017), in which the predictors are fitted as smooth factors (see Alberton et al. 2019; Camargo et al. 2018). Because there was autocorrelation between the predictor variables, we set one model for each predictor separately and one null model. Then, the relative importance of each model was compared using their AICc values to choose the best model, which had the lowest AICc value among them. We evaluated the significance of each predictor variable by comparing the R^2 of each model and F-test. To fit the GAM models, we used the mgcv package from R software (*v.1.8-28*; Wood 2019). Because we aimed to understand the phenological responses to climatic variables at the community scale and for the species represented by the two functional groups of wood density, we performed the analysis described above in two steps: First, for the community of each site using the Gcc index extracted of the community ROI and second, for the Gcc extracted of the ROIs of individuals of species with low and high wood density, separately. We conducted all analysis in R (R Core Team 2017).

Results

We sampled 126 individuals in our images across the three sites, these individuals encompass 22 tree species from 8 families (Table 1; Table SII), resulting in 5 individuals by species on average. The phenological metrics start, end and length of growing season was registered for 13 species in Petrolina, seven species in Serra Talhada and nine species in São João (Table 1). Among the most abundant species in our phenological sampling were *Cenostigma microphyllum*, *C. nordestinum*, *Senegalia bahiensis*, *Commiphora leptophloes*, *Mimosa tenuiflora*, *Sapium glandulosum* and *Aspidosperma pyrifolium* (Table SII). Three of them (*C. leptophloes*, *A. pyrifolium* and *S. glandulosum*) are among the five most frequent species in 31 plots set up for floristic survey across the northeast region of Brazil (unpublished data), also conducted in the ambitus of the Nordeste Project (Moonlight et al. 2020) developed in collaboration by the FAPESP and NERC foundations.

Leaf phenology and growing seasons across sites

The length of the growing season at the community level varied from 193 days for PET to 261 days for STA (Table 1). The LOS for the community was shorter during the first growing season (2017/2018) than the second (2018/2019) in the three sites (Table 1), despite the lower rainfall in 2019 (see sites description in Methods section). Surprisingly, the LOS at the community scale was similar among sites being more similar between the most arid site PET and the less arid site SJO (Table 1).

All individuals from the species monitored were deciduous in the three sites (Table 1; Fig. 3), but the length of growing season overall increased from the driest to the moist site. The length of growing season was highly variable among sites and species within the same site. Species from the most arid site Petrolina had shortest growing season compared to the less arid sites of Serra Talhada and São João (Table 1; Fig. 3). In PET, the length of growing season ranged from 34 (*C. conduplicatus)* to 235 days (*S. tuberosa);* STA length of growing season ranged from 160 (*M. urundeuva)* to 258 days (*A. colubrina*); and in SJO, the growing season length ranged from 158 (*S. glandulosum)* to 284 days (*Z. joazeiro)*, with the longest species-specific lengths of growing season (Table 1; Fig. 3). We registered three species (*A*. *colubrina, M*. *acutistipula* and *M*. *urundueva*) in the second growing season which

were not registered in the first growing season at STA (Table 1), due to a camera change of view in January 2018.

Table 1. Length of growing season, wood specific density (WSD) and wood density category of tree species from SDTF vegetation of Petrolina, Serra Talhada and São João municipalities in Pernambuco state of Brazil.

	Length of growing season (Days)		WSD ($mg\ mm^{-3}$)	WSD strategy
Site/Species	2017/2018	2018/2019		
Petrolina (13)				
Community	193	243		
Aspidosperma pyrifolium Mart. & Zucc.	157.5 ± 27.58	204 ± 38.18	0.61 ± 0.13	High
Cenostigma microphyllum (Mart. Ex G. Don)	147 ± 16.80	86.28 ± 38.28	0.79 ± 0.13	High
Cnidoscolus quercifolius Pohl	168.67 ± 26.50	231 ± 6.56	0.48 ± 0.07	Low
Commiphora leptophloeos (Mart.) J.B.Gillett	156.43 ± 8.06	178.29 ± 41.48	0.32 ± 0.07	Low
Croton conduplicatus Kunth	146 ± 7.07	34 ± 4.71	0.84 ± 0.05	High
Handroanthus spongiosus (Rizzini) S.Grose	196 ± 4.24	250 ± 2.83	0.73 ± 0.07	High
Manihot carthagenensis (Jacq.) Müll.Arg.	151 ± 2.12	122.5 ± 116.67	0.47 ± 0.19	Low
Mimosa tenuiflora (Willd.) Poir.	163.5 ± 14.85	147.25 ± 70.36	0.77 ± 0.41	High
Myracrodruon urundeuva M. Allemão	176	235	0.68 ± 0.05	High
Sapium glandulosum (L.) Morong	150.67 ± 12.83	174.33 ± 46.08	0.41 ± 0.13	Low
Schinopsis brasiliensis Engl.	125	91	0.86 ± 0.28	High
Senegalia polyphylla (DC.) Britton & Rose	205	103	0.74 ± 0.09	High
Spondias tuberosa Arruda	186	235	0.60 ± 0.10	High
Serra Talhada (7)				

Community	241	261		
Amburana cearensis (Allemão) A.C.Sm	177.5 ± 10.60	189 ± 2.12	0.43	Low
Anadenanthera colubrina var. *cebil* (Griseb.) Altschul		258.33 ± 2.52	0.74 ± 0.09	High
Aspidosperma pyrifolium Mart. & Zucc.	224.71 ± 38.43	211.14 ± 35.81	0.61 ± 0.13	High
Cenostigma nordestinum E. Gagnon & G.P. Lewis	218.57 ± 24.02	246.59 ± 13.97	0.68 ± 0.18	High
Commiphora leptophloeos (Mart.) J.B.Gillett	167.30 ± 23.49	165.40 ± 62.34	0.32 ± 0.07	Low
Mimosa acutistipula (Mart.) Benth.		167 ± 118.79	0.8	High
Myracrodruon urundeuva M. Allemão		160.25 ± 72.61	0.68 ± 0.05	High
São João (9)				
Community	205	248		
Commiphora leptophloeos (Mart.) J.B.Gillett	164.5 ± 46.71	204.20 ± 56.65	0.32 ± 0.07	Low
Croton heliotropiifolius Kunth	188	236	0.81± 0.03	High
Mimosa tenuiflora (Willd.) Poir.	219.56 ± 18.37	243.14 ± 28.59	0.77 ± 0.41	High
Guapira tomentosa (Casar.) Lundell	267	294	0.67 ± 0.16	High
Sapium glandulosum (L.) Morong	158 ± 28.28	178	0.41 ± 0.13	Low
Schinopsis brasiliensis Engl.	234.33 ± 146.65	281 ± 31.19	0.86 ± 0.28	High
Senegalia bahiensis (Benth.) Seigler & Ebinger	162.82 ± 45.30	215.92 ± 35.67	0.74	High
Senna sp. Mill.	210 ± 2.83	268.50 ± 20.51	0.76 ± 0.07	High
Ziziphus joazeiro Mart.	284	278	0.67 ± 0.04	High

Length of growing season and WSD data are mean ± SD. Wood density category: low-density species (<0.5) and high-density species (>0.5).

Environmental cues to leaf phenology

The tree communities of all three sites showed a very distinct seasonal pattern of leaf flushing during the rainy season (Fig. 3). The greenness onset (SOS) occurred after the end of the dry seasons of 2017 and 2018, as a response to the first rainfall pulses but differed areas among sites (Fig. 3). In PET and STA the community Gcc increased abruptly just after the first rainfall pulses at the onset of the rainy season (Fig. 3). At SJO the community Gcc increased smoothly, evidencing the less seasonal leafing pattern (Fig. 3). Indeed, the SOS dates were synchronic among species and concentrated in the beginning of the rainy season at PET and STA, but much more variable among species at SJO (Fig. 3).

The green down pattern or EOS was not as synchronic as the SOS and also differed between sites (Fig. 3). In PET and SJO the EOS occurred concomitantly with the decrease in rainfall, though the decline in the community Gcc was more abrupt in PET. The STA community Gcc decreased when rainfall was still high (see Fig. 3; February/2018 and March/2019), though the Gcc did not reach the low values of the dry season (Fig. 3). The decrease in STA community Gcc occurred during the rainy season, when most plants were still with mature leaves.

The species phenology, wood density

Species with low wood density showed a tendency for a shorter growing season in STA and SJO, but not in PET (Fig. 3). However, the SOS did not differ among species from the wood density functional groups in PET (GLMM; estimate=-17.05, P=0.15), STA (GLMM; estimate=-7.48, P=0.61) and SJO (GLMM; estimate=21.94, P=0.06), showing that the leaf flushing did not occur earlier for the low wood density species in comparison to the high wood density species in these sites. Although species with low wood density showed a tendency of earlier end of growing season in relation to the species with high wood density in STA and SJO (Fig. 3), these differences were not significant for STA (GLMM; estimate=-18.03, P=0.44) and SJO (GLMM; estimate=-23.56, P=0.10). Additionally, species from the low and high wood density functional groups in PET did not differ in EOS (GLMM; estimate=9.94, P=0.50).

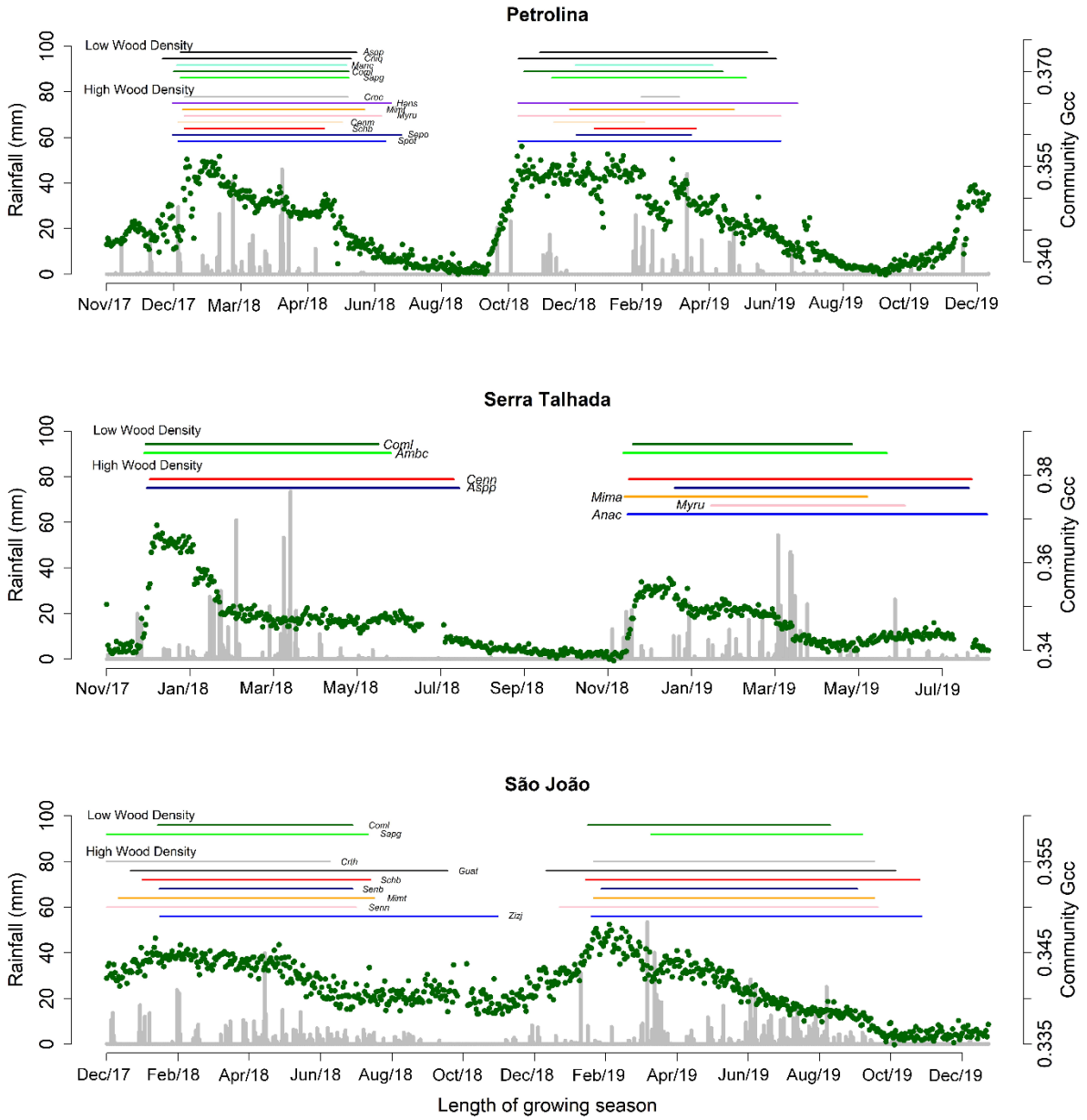


Figure 3. Caatinga community leafing patterns (Gcc, green dots), and the average length of growing season of low and high wood density species (color lines) at Petrolina, Serra Talhada and São João study sites, Northeastern Brazil, during the growing seasons of 2017/2018 and 2018/2019. Grey bars = accumulated daily rainfall (mm). Species acronyms: *Aspp = A. pyrifolium, Cniq = C. quercifolius, Manc = M. carthagenensis, Coml = C. leptophloeos, Sapg = S. glandulosum, Croc = C. conduplicatus, Hans = H. spongiosus, Mimt = M. tenuiflora, Myru = M. urundeuva, Cenm = C. microphyllum, Schb = S. brasiliensis, Sepo = S. polyphylla, Spot = S. tuberosa, Ambc = A. cearensis, Cenn = C. nordestinum, Mima = M. acutistipula, Anac = A. colubrina, Crth = C. heliotropiifolius, Guat = G. tomentosa, Senb = S. bahiensis, Senn = Senna, Zizj = Z. joazeiro.*

Environmental factors affecting the leafing patterns of the community and species functional groups

In order test the effects of the environmental factors in the leafing patterns of the community and of the functional groups of species with high and low wood densities, we summarized the results of GAM models, showing only the first- and second-best models, since the R^2 values of the remaining models were low ($R^2 < 0.10$; see supplementary material SIII for the full comparisons). Amongst the environmental factors analyzed in the GAM models, soil moisture was the most important predictor of the Gcc patterns for all sites (Table 2) at the community level and for both high and low wood density functional groups. The exception was for the low wood density species from STA, for which day-length was the most important predictor (Table 2).

The second-best predictor of Gcc at the community level was day-length, excepting for SJO, where the temperature had the best fit (Table 2). When analyzing the response of high wood density species, VPD was the second-best predictor of Gcc in the most arid sites PET and STA, while day-length was the second-best predictor at SJO (Table 2). The second-best predictor of the Gcc response of low wood density species was day-length for PET and SJO and soil moisture for STA (Table 2). It is important to note that the R^2 values may be low for some of the second models (Table 2), but it is also important to consider that they are single variable models, so the contribution to each variable may be significant since they might explain alone a certain amount of variation in the Gcc.

Table 2. Result of GAM Models for the effects of soil moisture, day-length, VPD and average daily temperature on the leafing patterns (Gcc) of the communities and species with low and high wood densities of three sites (Petrolina, Serra Talhada and São João) from Pernambuco state, Northeastern Brazil.

Site/Wood strategy	Predictor	edf	F-test	AICc	DE (%)	R^2
Petrolina						
Community	Soil Moisture (m^3 m^{-3})	23.57	11.27	1776.60	47.5	0.46
	Day-length (hours)	4.735	3.827	2040.20	22.8	0.23
	Null model			2231.73	0	0.00
High density	Soil Moisture (m^3 m^{-3})	36.77	41.14	30465.38	17.7	0.17
	VPD (kPa)	39.84	20.89	31502.18	10	0.10
	Null model			32629.19	0	0.00
Low density	Soil Moisture (m^3 m^{-3})	43.11	71.64	30595.40	26.3	0.26
	Day-length (hours)	28.82	23.09	32914.94	10.4	0.10
	Null model			34172.50	0	0.00
Serra Talhada						
Community	Soil Moisture (m^3 m^{-3})	15.09	9.476	660.98	54.5	0.53
	Day-length (hours)	9.39	2.463	902.01	24.2	0.23
	Null model			1017.69	0	0.00
High density	Soil Moisture (m^3 m^{-3})	40.54	155.6	47262.70	31.3	0.31
	VPD (kPa)	52.12	35.05	52873.69	9.48	0.09
	Null model			54789.27	0	0.00
Low density	Day-length (hours)	18.8	49.73	13740.11	33.3	0.33
	Soil Moisture (m^3 m^{-3})	32	25.95	14776.05	20.9	0.21

	Null model			16104.35	0	0.00
São João						
Community	Soil Moisture (m^3 m^{-3})	13.41	6.645	1885.42	27.4	0.26
	Average Temperature (°C)	2.283	0.919	2042.44	7.16	0.07
	Null model			2091.69	0	0.00
High density	Soil Moisture (m^3 m^{-3})	27.9	145	59730.02	20	0.20
	Day-length (hours)	10.08	36.93	62683.35	8.76	0.09
	Null model			64752.00	0	0.00
Low density	Soil Moisture (m^3 m^{-3})	23.04	43.24	21471.31	17.5	0.17
	Day-length (hours)	6.102	14.04	22197.10	9.35	0.09
	Null model			22978.45	0	0.00

The models are ordered from the lowest to the highest AICc. Excepting the null models, all models had statistical significance of $p < 0.001$. DE, deviance explained.

The Gcc was very sensitive to small changes in soil moisture in PET and STA at the community scale, changing abruptly in response to increases in soil moisture from 0.06 to 0.08, and 0.05 to 0.07, in PET and STA (Fig. 4), respectively. Also, small values of soil moisture (<0.15) were enough to keep Gcc high in these areas (Fig. 4). On the other hand, in SJO the changes in Gcc in response to soil moisture showed a smoother pattern, even though the values of soil moisture were much lower than in PET and STA (Fig. 4). The pattern of Gcc response to soil moisture was not different for the high and low wood density species in PET and SJO, but in STA, the day-length was the most important predictor for Gcc changes for the low wood density species (Table 2; Fig. 4). Changes in day-length from 12 to 12.6 hours triggered a gradual increase in Gcc for the low wood density species from STA (Fig. 4), while the high wood density species followed the same pattern of the community (Fig. 4).

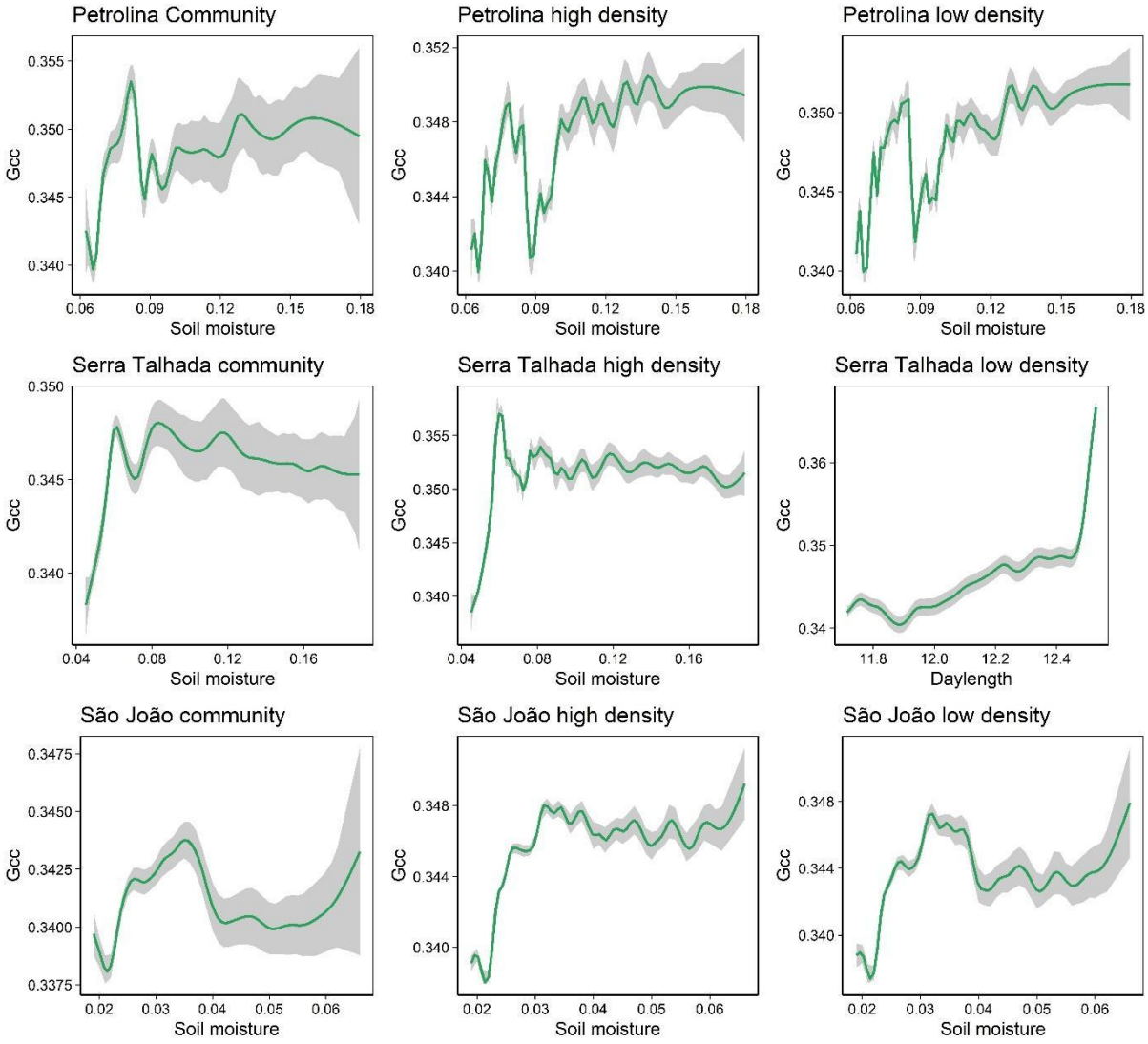


Figure 4. Predictors of Gcc changes of the best-model selected in GAM analysis fitted for the community and for the functional group of species with high and low wood densities from Petrolina, Serra Talhada and São João sites, Northeastern Brazil. The best predictors were the soil moisture and daylength. The green lines are the responses of Gcc fitted in the GAM analysis and the gray shades are their 95% confidence intervals.

Discussion

In this study we described the dominant leaf exchange strategies of tree species and their main climatic drivers across the gradient of aridity in the New World's largest SDTF, the Brazilian Caatinga. We tracked the leaf flush and fall at a fine temporal daily frequency by using phenocams and also tested if the leafing patterns were related to species woody density. We showed that all species were fully deciduous and the rainfall variability across sites influenced the duration of the growing season.

The specie's length of growing season increased towards the increase of rainfall from PET to STA and SJO. We demonstrated that, despite the differences in rainfall patterns, soil moisture was the main environmental driver of the community leaf exchange patterns across sites. However, the SOS was more synchronous among species from the driest sites. Finally, we found no relationship between the leaf flush and fall patterns and species' wood specific density.

All 22 species studied were deciduous, an expected result for Caatinga vegetation. Evergreen species accounting from 2% to 15.3% of the Caatinga species (Machado et al. 1997; Amorim et al. 2009; Lima & Rodal 2020; Lima et al. 2012; de Oliveira et al. 2015). Our study sites comprise SDTFs harsh conditions for leaf maintenance (Araújo et al. 2007), with low total annual mean precipitation, long periods of drought and elevated mean temperatures. The outcome is the predominance of deciduity, a strategy likely related to the variability and uncertainty in precipitation, that come in modest amounts, and the duration and intensity of dry season, all factors known influencing the species' leaf exchange strategies and degree of deciduousness (Alberton et al. 2019).

Aridity but not wood density influences the leafing patterns

All the species monitored in our study were deciduous, but the duration of growing season (LOS) of species increased towards a less arid site (SJO). The caatinga trees generally do not have a deep root system (Costa et al. 2014) to access subsoil water reserves and the differences in leafing patterns observed across sites were probably related to differences in the input of moisture through the rainfall. Differences in leafing patterns among sites were also found in other dry forests but they were related to differences in soil moisture across sites and the trees' access to the subsoil water table determined by root depth (Borchert 1994; Valdez-Hernández et al. 2010; Méndez-Alonzo et al. 2013).

The species SOS were synchronous, at the beginning of the rainy season, flushing shortly as a response to the first rainfall pulses after the dry season, in the dryer sites, PET and STA, while species SOS were more asynchronous in SJO, the moister site. The fast and synchronic flushing after small pulses of rainfall is a pattern observed in tree species of Caatinga (Machado et al. 1997; Amorim et al.

2009; Alberton et al. 2019). The fast, synchronous response of tree species of arid sites detected by phenocams in our study sites and by Alberton et al. (2019) at Petrolina, represents an adaptive strategy to cope with the unpredictability of the rainfall. The species flushing shortly after the first rainfall events can be photosynthetically active early, developing fast in the shoer growing season. One characteristic of Caatinga is its erratic nature of rainfall (Sampaio 1995) with high interannual variability, resulting in unpredictability of start, duration, and amount of rainfall in the rainy season, mainly in the drier regions (Souza et al. 2016). The smother pattern of Gcc for the community and less synchronic SOS among species we found in SJO was a characteristic of a less seasonal environment, indicating that fast leaf flushing is a trait selected only in drier sites.

The leaf fall was highly variable and less synchronic among species than the leaf flushing in all sites studied. The variation in the period of leaf fall has been observed for Caatinga tree's species (Machado et al. 1997; Amorim et al. 2009; Lima & Rodal 2010; Lima et al. 2012). The time of leaf shedding may be associated to species wood density and as a strategy of water economy (Lima & Rodal 2010; Lima et al. 2012; de Oliveira et al. 2015). Shed leaves before the cessation of the rains in species with low wood density has been suggested as a strategy to store water allowing to flush new leaves earlier in the following rainy season (Lima et al. 2012; de Oliveira et al. 2015). We tracked leaf phenology in a daily basis, detecting even small differences among individuals and species. Contrary to what was expected and described, we did not find differences neither in leaf flushing nor the leaf fall among species with low and high wood density across the three sites. We consider the capacity to keep leaves longer after the cessation of rains in trees of SDTF is determined by several factors, including the access to the deeper soil water reserves (e.g. *Capparis scabrida* in Butz et al. 2018), soil moisture variations (Borchert 1994; Valdez-Hernández et al. 2010; Méndez-Alonzo et al. 2013), and not only wood density.

Soil moisture drives the leafing patterns across sites

Amongst the environmental factors, soil moisture was the best predictor of the Gcc patterns for the three sites at the community scale. The Caatinga SDTF is a seasonal and strongly water limited

environment and our results indicate that the water available to the plants in the soil is the main driver of the leafing patterns. The abrupt increase in the community Gcc and its pattern after small increases in soil moisture in PET and STA, shows that their plant communities have a quick leaf flushing and a very seasonal leafing pattern which strongly relies upon the soil moisture. On the other hand, the smother pattern found in the community Gcc in SJO, indicates that leafing patterns of its plant community is the less seasonal and less dependent of moisture among sites. Intriguingly, although rainfall is higher in SJO, its soil moisture is the lowest among the sites. The soils in SJO have 87.7% of sand (Brito et al. 2020), which influences its capacity to retain water, contrasting with the 65% of sand in STA (Silva et al. 2017) and 75.89 % of sand in PET (Alexandre Brunello, unpublished data). Surprisingly, the daily rainfall was not selected as a predictor in the best models, however it is what ultimately influences the soil moisture, explaining the strong seasonal patterns in the sites with low rainfall and the less seasonal pattern in the site with the highest rainfall pattern.

Our findings indicate that aridity constrains the species' length of growing season with the most arid sites presenting the shorter LOS. The strong aridity resulted in species' synchronic flushing, while the leaf fall was less synchronic among species regardless of site aridity. The species wood density was not a determinant functional trait for their SOS and EOS across sites. The available moisture in the soil is the main driver of phenological responses of the Caatinga tree communities regardless of site aridity but their phenological patterns were more seasonal in sites where rainfall is lower, PET and STA, when compared to the moister site, SJO. The available moisture in the soil was also the main driver of phenological responses of species from both functional groups of wood density in all sites, excepting for species with low wood density from STA, for which the day-length was the main driver.

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Supplementary material

Table SI. Sample size for wood density of trees from municipalities from Petrolina, Serra Talhada and São João municipalities of Pernambuco state, Brazil.

	Number of individuals per site		
Species	Petrolina	Serra Talhada	São João
Commiphora leptophloeos (Mart.) J.B.Gillett	7	6	2
Sapium glandulosum (L.) Morong	11	7	
Amburana cearensis (Allemão) A.C.Sm		1	
Manihot carthagenensis (Jacq.) Müll.Arg.	10	6	
Cnidoscolus quercifolius Pohl	5		
Spondias tuberosa Arruda	7	5	1
Aspidosperma pyrifolium Mart. & Zucc.	8	12	
Ziziphus joazeiro Mart.			
Guapira tomentosa (Casar.) Lundell			
Cenostigma nordestinum E. Gagnon & G.P. Lewis		10	
Myracrodruon urundeuva M. Allemão		5	
Handroanthus spongiosus (Rizzini) S.Grose	9		
Anadenanthera colubrina var. cebil (Griseb.) Altschul		8	
Senegalia polyphylla (DC.) Britton & Rose	12	7	
Senna sp. Mill.			2
Mimosa tenuiflora (Willd.) Poir.	2		
Cenostigma microphyllum (Mart. Ex G. Don)	9		
Mimosa acutistipula (Mart.) Benth.			
Croton heliotropiifolius			
Croton conduplicatus Kunth	2		
Schinopsis brasiliensis Engl.	3		

Table SII. Number of individuals by species sampled in the phenocam images from Petrolina, Serra Talhada and São João municipalities of Pernambuco state, Brazil.

		Number of individuals per site and growing season					
		Petrolina		Serra Talhada		São João	
Species	Family	2017-2018	2018-2019	2017-2018	2018-2019	2017-2018	2018-2019
Commiphora leptophloeos (Mart.) J.B.Gillett	Burseraceae	7	7	10	12	8	5
Sapium glandulosum (L.) Morong	Euphorbiaceae	6	6			2	1
Amburana cearensis (Allemão) A.C.Sm	Leguminoseae			2	2		
Manihot carthagenensis (Jacq.) Müll.Arg.	Euphorbiaceae	2	2				
Cnidoscolus quercifolius Pohl	Euphorbiaceae	3	3				
Spondias tuberosa Arruda	Anacardiaceae	1	1				
Aspidosperma pyrifolium Mart. & Zucc.	Apocynaceae	2	2	7	7		
Ziziphus joazeiro Mart.	Rhamnaceae					1	1
Guapira tomentosa (Casar.) Lundell	Nyctaginaceae					1	1
Cenostigma nordestinum E. Gagnon & G.P. Lewis	Leguminoseae			21	22		
Myracrodruon urundeuva M. Allemão	Anacardiaceae	1	1		9		
Handroanthus spongiosus (Rizzini) S.Grose	Bignoniaceae	2	2				
Anadenanthera colubrina var. cebil (Griseb.) Altschul	Leguminoseae				3		
Senegalia polyphylla (DC.) Britton & Rose	Leguminoseae	1	1				

Senna sp. Mill.	Leguminoseae					2	2
Mimosa tenuiflora (Willd.) Poir.	Leguminoseae	2	2			9	7
Cenostigma microphyllum (Mart. Ex G. Don)	Leguminoseae	6	6				
Mimosa acutistipula (Mart.) Benth.	Leguminoseae				2		
Croton heliotropiifolius	Euphorbiaceae					1	1
Croton conduplicatus Kunth	Euphorbiaceae	2	2				
Schinopsis brasiliensis Engl.	Anacardiaceae	1	1			3	3
Senegalia bahiensis (Benth.) Seigler & Ebinger	Leguminoseae					11	12
Total		36	36	40	57	38	33

Table SIII. Effects of Soil moisture, day-length, VPD, rainfall and average daily temperature on the leafing patterns (Gcc) of the communities and species with low and high wood densities of sites from Pernambuco state, Brazil.

Site/Wood density strategy	Predictor	edf	F-test	AICc	ΔAIC	R^2
Petrolina						
Community	Soil Moisture (m3 m-3)	23.57	11.27	1776.60		0.46
	Day-length (hours)	4.735	3.827	2040.20	263.60	0.23
	Average Temperature (°C)	6.639	1.187	2174.65	398.04	0.08
	VPD (kPa)	4.583	0.844	2189.71	413.11	0.06
	Rainfall (mm)	2.846	0.597	2207.16	430.56	0.04
	Null model			2231.73		0.00
High	Soil Moisture (m3 m-3)	36.77	41.14	30465.38		0.17
	VPD (kPa)	39.84	20.89	31502.18	1036.80	0.10
	Rainfall (mm)	11.65	16.8	31927.39	1462.01	0.06
	Day-length (hours)	22.82	8.676	32154.07	1688.69	0.04
	Average Temperature (°C)	35.43	7.786	32226.77	1761.39	0.04
	Null model			32629.19		0.00
Low	Soil Moisture (m3 m-3)	43.11	71.64	30595.40		0.26
	Day-length (hours)	28.82	23.09	32914.94	2319.54	0.10
	VPD (kPa)	49.97	22.22	32980.08	2384.68	0.10
	Average Temperature (°C)	49.5	16.69	33278.22	2682.82	0.08
	Rainfall (mm)	25.49	21.22	33301.32	2705.92	0.07
	Null model			34172.50		0.00
Serra Talhada						
Community	Soil Moisture (m3 m-3)	15.09	9.476	660.98		0.53
	Day-length (hours)	9.39	2.463	902.01	241.03	0.23
	VPD (kPa)	2.389	0.666	983.47	322.49	0.07
	Average Temperature (°C)	2.754	0.294	1004.95	343.97	0.03
	Rainfall (mm)	3.051	0.162	1013.75	352.77	0.02

	Null model			1017.69		0.00
High	Soil Moisture (m3 m-3)	40.54	155.6	47262.70		0.31
	VPD (kPa)	52.12	35.05	52873.69	5610.99	0.09
	Average Temperature (°C)	48.72	20.77	53650.52	6387.82	0.06
	Rainfall (mm)	46.88	16.48	53888.68	6625.98	0.05
	Day-length (hours)	15.77	15.4	53917.93	6655.23	0.04
	Null model			54789.27		0.00
Low	Day-length (hours)	18.8	49.73	13740.11		0.33
	Soil Moisture (m3 m-3)	32	25.95	14776.05	1035.94	0.21
	Rainfall (mm)	42.97	7.892	15702.84	1962.73	0.07
	Average Temperature (°C)	41.55	7.842	15705.71	1965.60	0.07
	VPD (kPa)	41.66	6.519	15776.21	2036.10	0.06
	Null model			16104.35		0.00
São João						
Community	Soil Moisture (m3 m-3)	13.41	6.645	1885.42		0.26
	Average Temperature (°C)	2.283	0.919	2042.44	157.02	0.07
	VPD (kPa)	3.525	0.805	2050.06	164.64	0.06
	Day-length (hours)	2.583	0.251	2080.90	195.48	0.02
	Rainfall (mm)	1.15	0.082	2088.99	203.57	0.01
	Null model			2091.69		0.00
High	Soil Moisture (m3 m-3)	27.9	145	59730.02		0.20
	Day-length (hours)	10.08	36.93	62683.35	2953.33	0.09
	VPD (kPa)	50.71	29.31	63137.78	3407.76	0.07
	Rainfall (mm)	10.06	11.29	64109.48	4379.46	0.03
	Average Temperature (°C)	54.83	11.43	64143.59	4413.57	0.03
	Null model			64752.00		0.00
Low	Soil Moisture (m3 m-3)	23.04	43.24	21471.31		0.17

Day-length (hours)	6.102	14.04	22197.10	725.79	0.09
VPD (kPa)	41.95	10.24	22441.43	970.12	0.07
Rainfall (mm)	5.07	2.718	22827.40	1356.09	0.02
Average Temperature (°C)	14.85	1.715	22900.14	1428.83	0.01
Null model			22978.45		0.00

The models are ordered from the lowest to the highest AICc. Excepting the null models, all models had statistical significance of $p < 0.001$.