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'Pre-rain green-up is ubiquitous across southern tropical Africa: implications for temporal niche separation and model representation

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1 **Pre-rain green-up is ubiquitous across southern tropical Africa: implications for**
2 **temporal niche separation and model representation**

3

4 Short running title: The precocious phenology of southern Africa

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16

17 **Summary**

- 18 • Tree phenology mediates land-atmosphere mass and energy exchange
19 and is a determinant of ecosystem structure and function. In the dry
20 tropics, including African savannas, many trees grow new leaves during
21 the dry season – weeks or months before the rains typically start. This
22 syndrome of pre-rain green-up has long been recognised at small scales,
23 but the high spatial and interspecific variability in leaf phenology has
24 precluded regional generalisations
- 25 • We use remote sensing data to show that this precocious phenology is
26 ubiquitous across the woodlands and savannas of southern tropical
27 Africa.
- 28 • In 70% of the study area, green-up preceded rain onset by > 20 days
29 (42% >40 days). All the main vegetation formations exhibit pre-rain
30 green-up, by as much as 53 ± 18 days (in the wet miombo). Green-up
31 shows low interannual variability (SD between years = 11 days), and high
32 spatial variability (>100 days)
- 33 • These results are consistent with a high degree of local phenological
34 adaptation, and an insolation trigger of green-up. Tree-tree competition
35 and niche separation may explain the ubiquity of this precocious
36 phenology. The ubiquity of pre-rain green-up described here challenges
37 existing model representations and suggests resistance (but not
38 necessarily resilience) to the delay in rain onset predicted under climate
39 change.

40

41 Keywords: Leaf phenology, rain onset, miombo, mopane, tree-tree competition,
42 tree-grass competition

43

44 Introduction

45 The timing of leaf emergence in tree species mediates land-atmosphere
46 mass and energy exchanges and is an important determinant of ecosystem
47 structure and function (Richardson *et al.*, 2013; Xia *et al.*, 2015). However, in the
48 dry tropics, phenological data are sparse and the processes controlling leaf
49 emergence are not well understood (Richardson *et al.*, 2013). Existing work
50 documents a wide range of phenological syndromes ranging from deciduous
51 through brevideciduous to evergreen (Williams *et al.*, 1997; de Bie *et al.*, 1998;
52 Singh & Kushwaha, 2005) and a large degree of spatial, inter- and intra-specific
53 variability (de Bie *et al.*, 1998; Shackleton, 1999; Higgins *et al.*, 2011)

54 Many ecological studies report the intriguing (Borchert, 1994; Archibald
55 & Scholes, 2007) phenomenon of *pre-rain green-up* i.e. the appearance of new
56 leaves towards the end of the dry season, but before the start of the wet season.
57 This phenological syndrome has been recorded in the dry forests of the
58 Neotropics (Borchert, 1994), South East Asia (Elliott *et al.*, 2006) and in the
59 savanna woodlands of Australia (Williams *et al.*, 1997; Myers *et al.*, 1998). In
60 Africa, studies have documented pre-rain green-up in mesic woodlands (Ernst &
61 Walker, 1973; Hall-Martin & Fuller, 1974; Malaisse, 1974; Guy *et al.*, 1979; Frost
62 & Campbell, 1996; Devineau, 1999; Chidumayo, 2001; Simioni *et al.*, 2004; Ryan
63 *et al.*, 2014), semi-arid savannas (Childes, 1988; de Bie *et al.*, 1998; Archibald &
64 Scholes, 2007; Higgins *et al.*, 2011) and arid savannas (Do *et al.*, 2005).

65 The reasons for pre-rain green-up are not fully understood. However, the
66 suggested benefits include: 1) The avoidance of herbivory during the vulnerable
67 stage of leaf expansion, due to reduced insect activity in the dry season (Aide,
68 1988); 2) avoidance of rain-induced leaching of the nutrient-rich, immature
69 leaves (Sarmiento *et al.*, 1985); 3) optimisation of photosynthetic gain during the
70 wet season (Kikuzawa, 1995; Reich, 1995); 4) being ready to fully exploit, and
71 compete for, rain-induced soil nutrient availability (Scholes & Walker, 2004;
72 Archibald & Scholes, 2007); 5) a longer growing season (Scholes & Walker,
73 2004). However, several costs must be set against these benefits: pre-rain green-
74 up has been linked to the ability to access deep soil moisture (Borchert, 1994) or
75 groundwater (Do *et al.*, 2008), and to the storage of water in tree stems

76 (Borchert, 1994), but these mechanisms require substantial investments in
77 hydraulic architecture and therefore confer large construction and maintenance
78 costs. Furthermore, utilising deep water at the height of the dry season requires
79 a costly, embolism-resistant hydraulic system (Eamus, 1999). Most seasonally
80 dry ecosystems are highly flammable in the late dry season, presenting an
81 additional risk to new leaves (Frost & Campbell, 1996).

82 Understanding the extent and frequency of pre-rain green-up is important
83 for several reasons. Firstly, prognostic models of the land surface need to be able
84 to represent tree leaf phenology if they are to accurately describe land-
85 atmosphere fluxes (Richardson *et al.*, 2013). Currently, because of weak process
86 understanding, even “state of the art” Africa-specific dynamic global vegetation
87 models (DGVMS) assume all trees are facultatively deciduous, even though the
88 many observations of pre-rain green-up suggest that some trees may be
89 obligately deciduous (Scheiter & Higgins, 2009); other models use a simple soil
90 water threshold (Cramer *et al.*, 2001). Neither of these approaches can be
91 expected to represent the relationship between tree leaf phenology and a
92 changing climate (Seth *et al.*, 2013) in a system where pre-rain green-up is
93 common. Finally, temporal niche separation is a fundamental process by which
94 inter-specific competition structures tropical ecosystems (Pau *et al.*, 2011). Both
95 tree-tree and tree-grass competition are likely to play a role in the phenology of
96 savanna ecosystems, but as yet there has been no regional analysis comparing
97 pre-rain green-up in floristically different savanna systems.

98 As a step towards improved understanding of pre-rain green-up, and thus
99 process-based modelling, a better understanding of its biogeography is needed
100 (Guan *et al.*, 2014b). To date this has been hindered by the high variability in
101 phenological characteristics: which vary between and within species (de Bie *et*
102 *al.*, 1998), with climate (White, 1983; Chidumayo, 2001), short term weather
103 patterns like droughts (Borchert, 2008) and catenary position (Shackleton,
104 1999; Fuller, 1999). These multiple scales of temporal and spatial variability
105 have hindered our ability to draw broad regional conclusions from field studies,
106 and highlight the need for regional-scale analyses (Archibald & Scholes, 2007).
107 Here we present such an analysis, using the methods developed by Ryan *et al.*

108 (2014) to examine pre-rain green-up in Southern tropical Africa and analyse its
109 occurrence in different vegetation formations. Specifically, we ask:

- 110 1. What is the leaf phenology of the major floristic assemblages in southern
111 tropical Africa and how does it vary in time and space?
- 112 2. How common in time and space is the occurrence of pre-rain green-up?
- 113 3. For each floristic assemblage, what is the interannual and spatial variability
114 in green-up dates, and what factors can explain this variation?

115 We interpret the results of the study using ecological and evolutionary
116 explanations of phenological niche separation (Pau *et al.*, 2011) and theories of
117 savanna tree-grass coexistence (Chesson, 1985; Walker, 1987).

118 **Methods**

119 To understand the prevalence of pre-rain green-up we conducted a remote
120 sensing analysis of green-up dates and rain onset dates from 2°S to 23°S for the
121 African mainland, for each March-March year (2002-2014) using MODIS EVI (the
122 enhanced vegetation index acquired from the Moderate Resolution Imaging
123 Spectroradiometers; Huete 2002) and TRMM rainfall data (Tropical Rainfall
124 Measuring Mission; Kummerow et al. 1998).

125 **Green-up dates**

126 The definition and estimation of green-up dates uses the method corroborated in
127 these ecosystems by Ryan et al. (2014). The method utilises the fact that the land
128 surface phenology signal detected by satellite-borne sensors is closely related to
129 the tree leaf phenology in the period before the rains. This is because before the
130 rains, no substantial grass growth is possible (Chidumayo, 2001; Archibald &
131 Scholes, 2007). Given this, the method looks for the first detectable increase in
132 vegetation greenness (represented by EVI) each year. We use MODIS EVI
133 aggregated to a 0.05° lat/long grid (MOD and MYD 13C1.5, available from
134 LPDAAC). These two MODIS products, obtained by the Terra and Aqua satellites
135 respectively, composite daily acquisitions over 16 day periods, 8 days out of
136 synchrony with each other. We interleave the 16 day composites to improve the
137 temporal resolution of the time series.

138 Many definitions have been used to derive day of year of green-up (G_{DOY})
139 dates from reflectance and/or EVI data (Reed *et al.*, 1994; Zhang, 2005;
140 Archibald & Scholes, 2007; Bachoo & Archibald, 2007; Guan *et al.*, 2014a;
141 Buitenwerf *et al.*, 2015), with no consensus as to techniques. To help resolve this,
142 Ryan *et al.* (2014) tested four different methods of estimating G_{DOY} from EVI data
143 and compared them to ground-based hemispherical canopy photography at a
144 site in the woodlands of Mozambique. This showed that when using MODIS EVI
145 data the i) choice of G_{DOY} definition made only small differences to the estimated
146 G_{DOY} (max range 15 days), ii) that all methods were capable of detecting G_{DOY} at
147 some point between the annual min and 10% of the annual max in over 80% of
148 pixel-years, iii) that the backwards looking moving average definition of
149 Archibald & Scholes (2007) was most reliable at detecting G_{DOY} when used with
150 EVI data, and was conservative, tending to give later green-up dates than the
151 ground data. Thus in this study we present the results using the Archibald &
152 Scholes (2007) definition of green-up.

153 The estimation of day of year of green-up (G_{DOY}) is done for each pixel and
154 for each annual (March-March) time series (Archibald & Scholes, 2007; Ryan *et*
155 *al.*, 2014). First the data are smoothed with a Savatsky-Golay filter, using only
156 data with ‘good’ or ‘marginal’ pixel reliability. The Savatsky-Golay filter was
157 chosen as it minimised the tendency of some smoothing filters to shift green-up
158 to earlier dates. The smoothed data are fitted with a piecewise cubic Hermite
159 interpolation and the year’s minimum value is found. Based on Archibald &
160 Scholes (2007), searching forward from this point, G_{DOY} is indicated as occurring
161 at measurement i , when:

$$162 \quad p_i > \overline{p_{t-1\dots t-4}}$$

163 where p_i is the EVI value at time i and $\overline{p_{t-1\dots t-4}}$ is the mean EVI of the past
164 four observations.

165 This procedure was executed for each 0.05° pixel. D , the number of days
166 between green-up and rain onset, was calculated at the 0.05° resolution of the
167 MODIS data, with the 0.25° rainfall data (see below) interpolated using a cubic
168 spline.

169 **Rain onset dates**

170 For rainfall estimates we use data from the Tropical Rainfall Measuring Mission
171 (TRMM, Kummerow *et al.*, 1998). The 3B42 daily product uses a combination of
172 infra-red and microwave observations scaled to match monthly rain gauge
173 analyses (Huffman *et al.*, 2007). Data are available at 0.25° spatial resolution and
174 were extracted for the period 2002-2014 from the NASA Goddard Earth Sciences
175 Data and Information Services Center.

176 For rain onset detection, an approach similar to that for green-up dates
177 was followed. We use the daily TRMM data from 2002 (when data from both
178 MODIS sensors became available) to 2014 (when one instrument aboard TRMM
179 was switched off). For each year (March-March) and for each pixel, the month of
180 minimum rainfall is located, and the remainder of the time series is evaluated
181 until two criteria are met. The criteria are: (a) 10 days during which a total of 25
182 mm of rain falls, followed by (b) 20 days with > 20 mm total rain. These criteria
183 are based on Tadross (2005) and are designed to detect rainfall that allows the
184 start of maize cultivation. Thus we believe they are conservative with respect to
185 tree water requirements, but approximate those of grasses.

186 Green-up and rain onset frequencies were analysed by the major floristic
187 assemblages defined by the map of White (1983), which was created before
188 satellite data was available and is thus independent of the MODIS data. White's
189 map was downsampled from its original resolution of 30" by taking the mode to
190 0.25° resolution for comparison to the rainfall data, and to 0.05° for the
191 comparison to EVI and the estimation of the pre-rain green-up period (~5.4 km
192 at the centre of the study area). A description of the floristics and structure of
193 each vegetation type is included in supplementary Table S1.

194 We masked from our analysis pixels where we expect few trees to be
195 present, namely pixels that had more than 10% water; pixels with a maximum
196 EVI < 0.4; and pixels classed as wetlands, agriculture or urban in the MODIS
197 12C1 land cover product for 2001. Pixels with low seasonal variation in EVI
198 (range < 0.2) were also excluded, as evergreen systems are not amenable to the
199 analysis presented here. In areas without a distinct rainy season, the rain onset

200 algorithm detects no R_{DOY} – pixels where this occurred more than eight times
201 were also masked from the analysis.

202 **Results**

203 Pre-rain green-up is widespread across southern tropical Africa (Fig. 1
204 and 2). All the major vegetation types with a strong seasonal cycle of EVI show
205 pre-rain green-up, and the period between G_{DOY} and R_{DOY} , D , varied from a mean
206 of 27 ± 25 to 53 ± 18 days for the major vegetation types (Table 1). The number of
207 days by which green-up preceded rain onset on average (D), was > 0 days for
208 78% of the terrestrial study area; > 20 days for 70% of the study area; and > 40
209 days for 42% of the study area. 19% of the study area was masked, mainly
210 because of low EVI (9%) or low interannual variation in EVI (5%), anthropic
211 land cover (3%). R_{DOY} could not be detected in >8 years (of 13) in 2% of the
212 region.

213 Each year, the rains spread southeast from the Congo Basin arriving in
214 most of central southern Africa by DOY 300, and reaching the northeast and
215 southwest of the region last, around DOY 330 (Fig. 2). Northern Angola and the
216 Congo basin have earliest R_{DOY} from around DOY 250. Standard deviation (SD) in
217 R_{DOY} between the 13 years was <20 days for most of central southern Africa, but
218 more variable in the northeast and southwest coastal regions.

219 Green-up DOY (G_{DOY}) followed a broadly similar, but earlier, pattern,
220 occurring first in Angola, the Congo basin and parts of Zambia ($G_{DOY} \sim 200$) and
221 then moving south and east, reaching Zimbabwe, Botswana and Mozambique by
222 DOY 250-280 and occurring last along the Indian Ocean coast (DOY >300) (Fig.
223 2). Similar to R_{DOY} , G_{DOY} was least variable in the northwest and centre of the
224 study area (SD ~ 10 days), and SD was <30 days for all the study area except the
225 equatorial rainforest, and the southwest shrublands and semi-deserts.

226 **Differences between vegetation types**

227 Each (floristic) vegetation type had a distinctive time series of EVI, varying from
228 the relatively aseasonal rainforest (Fig. 1a), to the highly seasonal woodlands
229 and savannas (Fig. 1b-e). The wet miombo woodlands showed a clear and
230 sustained increase in EVI up to 2 months before rain onset, at which point there

231 was a much more rapid increase in EVI (Fig. 1b). The drier (miombo,
232 undifferentiated and mopane) woodlands had a less distinct pre-rain green-up,
233 but EVI still increased before R_{DOY} ($D = 39 \pm 17$, 33 ± 16 and 35 ± 15 respectively).
234 The *Acacia* savannas had by far the highest interannual variability in rain onset
235 date (23 days) and also green-up (34 days), but still on average showed pre-rain
236 green-up of 41 ± 14 days.

237 Within vegetation types, G_{DOY} was much more variable spatially than
238 between years (compare the widths of the pdfs to the vertical range of the
239 dashed lines in Fig. 3), with for example, wet miombo showing low interannual
240 variability (SD 11 days), but spatial variability in G_{DOY} from 205-297. Interannual
241 variability in G_{DOY} , expressed as the standard deviation of the 13 years of
242 observations, ranged from 11 days for wet miombo to 34 days for the *Acacia*
243 savannas (Table 1). For R_{DOY} , interannual variability ranged from 14 days in wet
244 miombo to 23 days in the *Acacia* savannas. In the miombo and lowland
245 rainforests, for a given pixel, green-up and rain onset dates showed no
246 relationship with each other (slope 0.01-0.06), whilst in the *Acacia* woodlands
247 types there was a weak relationship (slope 0.2-0.37), suggesting more plasticity
248 in these more arid and variable systems.

249 Our analysis used the rescaled vegetation map at 0.05° for the estimation
250 of green-up dates of each vegetation class (see methods). This resulted in 10% of
251 the 1 unmasked study area being comprised of pixels with a mixture of two
252 vegetation types. To check if these mixed pixels were different from the rest of
253 the vegetation type, we reran the analysis with and without the mixed pixels.
254 This showed that the mixed pixels had on average a similar green-up date to the
255 whole vegetation class, with the difference only exceeding 6 days for the drier
256 rain forests (where the mixed pixels G_{DOY} was 18 ± 45 (mean \pm SD) and the whole
257 vegetation type averaged 4 ± 48).

258 Discussion

259 Our results demonstrate that the precocious phenology of pre-rain green-
260 up is widespread across the region and occurs in all the major vegetation types.
261 There is high spatial variation in green-up dates within each vegetation type,

262 consistent with local adaptation, and, in the wetter parts of the region, there is
263 low interannual variability, suggesting an insolation (i.e. photoperiod or
264 irradiance) cue rather than a meteorological cue of green-up. These results,
265 alongside previous ground-based studies in the region (Hall-Martin & Fuller,
266 1974; Malaisse, 1974; Guy *et al.*, 1979; Childes, 1988; Chidumayo, 1994, 2001,
267 2015; Frost & Campbell, 1996; Archibald & Scholes, 2007; Richer, 2008a; Higgins
268 *et al.*, 2011; Ryan *et al.*, 2014) and one other remote sensing study (Guan *et al.*,
269 2014b), build a coherent picture of ubiquitous pre-rain green-up in the region.
270 This provides several challenges to current understanding and modelling of this
271 region's vegetation.

272 Firstly, the fact that trees are able to display leaves in very dry conditions,
273 e.g. 4-5 months since the last substantive rainfall, raises questions about tree
274 water use and access in the dry season. Leaf display in the dry season implies
275 substantial quantities of water stored in the tree or deep root access to
276 groundwater must be common. This in turn suggests that models of tree leaf
277 phenology based on surface soil moisture (e.g. in many DVGMs, Cramer 2001)
278 cannot capture the dominant tree phenology of the region, as clearly surface soil
279 moisture is weakly tied to leaf display across much of southern Africa (Fig 1).
280 Such models need to be adapted to incorporate pre-rain green-up to skilfully
281 represent land-atmosphere interactions in the late dry season.

282 Secondly, there appears to be an internal control on phenology unrelated
283 to weather conditions in most of the study region. This is evidenced by the low
284 interannual variability of green-up across the region (Fig 1) particular in the
285 wetter areas. We consider it implausible that a weather-related cue could have
286 such low interannual variability over a 13-year period as to lead to the mean of
287 11 days interannual variability in green-up in the wet miombo. This internal
288 control could be cued by insolation e.g. day length, or a related property such as
289 the timing of peak insolation (Rivera *et al.*, 2002; Borchert *et al.*, 2005). The large
290 spatial variability in green-up dates, even in vegetation types which are known to
291 be dominated by the same genera across their entire range (such as the miombo
292 (Frost & Campbell 1996)), is consistent with a high degree of local adaptation
293 (Phillimore *et al.*, 2010) to the timing of the rains. This is supported by the fact

294 that in the wetter vegetation types, mean dates of green-up and rain-onset are
295 correlated (e.g. in the wet miombo $G_{DOY} = 1.0 \times R_{DOY} - 55$, $p \ll 0.01$, $r^2 = 0.46$;
296 Table 1). The implications are intriguing: trees that have an insolation cue and a
297 high level of local adaptation are likely to show little change in green-up dates in
298 response to the predicted delays in rain onset resulting from climate change-
299 driven alterations to the African monsoon (Seth *et al.*, 2013), at least until some
300 ecophysiological threshold is exceeded (Richer, 2008b). Support for this idea
301 comes from a global analyses of phenological change which shows that African
302 woodlands have undergone comparatively little phenological change over the
303 last three decades (Buitenwerf *et al.*, 2015). Such resistance to climate change
304 does not imply resilience; the fitness consequences of delayed rain onset may be
305 significant, and might cause species turnover.

306 Thirdly, these observations show that the fundamental temporal niche for
307 savanna and woodland tree leaf display is rather large and includes the driest,
308 hottest part of the year. The realised temporal niche of many tree species is
309 much more restricted, i.e. Fig 1 shows sub-maximal leaf display for much of the
310 year in all vegetation types. Although precocious phenology is mostly discussed
311 in terms of its costs and benefits compared to rain-induced green-up (see
312 references in introduction), we discuss it here in terms of niche differentiation
313 leading to competitive advantage.

314 Two frameworks for thinking about competitive interactions and
315 phenology are the conceptual model of abiotic and biotic controls on phenology
316 presented in Pau *et al.* (2011), and the long-standing (Chesson, 1985; Walker,
317 1987; Scholes & Walker, 2004) temporal niche separation hypothesis sometimes
318 invoked to explain tree-grass coexistence in savannas. Under the Pau *et al.*
319 (2011) conceptual model, leaf display is presented as having fundamental
320 limitations imposed by abiotic factors (primarily climate) but, where these are
321 not limiting, being driven by inter-specific competitive processes, which drive
322 temporal niche separation. The abiotic factors are typically well represented in
323 models (Jolly *et al.*, 2005; Richardson *et al.*, 2013) and often invoked in the
324 description of the study region as “rain green” (Friend *et al.*, 2007) or “drought
325 deciduous”. Such abiotic models are however not sufficient in tropical systems

326 such as the study area: the ubiquity of pre-rain green-up implies no fundamental
327 limitation to the timing and period of tree leaf display in these systems. In the
328 (humid, equatorial) tropics, Pau et al's model invokes biotic competition to
329 explain the distinct phenological niche that most species occupy, which also
330 explains the predominance of solar radiation-driven phenological cues, as this is
331 the only reliable cue in the wet tropics (Borchert *et al.*, 2005). Such biotic
332 processes can be invoked to explain the patterns presented here: competition
333 pushes tree leaf display into the unfavourable, but feasible, dry season. This
334 could be competition between trees and grasses or between tree species. An
335 "arms race" might result, in which some trees specialise in pre-rain green-up, in
336 an attempt to avoid competition for nutrient, water or carbon acquisition. The
337 savanna temporal niche hypothesis would suggest that this is driven by tree-
338 grass competition for the rain-induced flush of nutrients (February & Higgins,
339 2016) rather than extending the photosynthetic period (Scholes & Walker,
340 2004); plausible given the dystrophication of the study region. However pre-rain
341 green-up is observed in dry forests and other ecosystems with no grass layer. We
342 therefore hypothesise that rain-green, facultatively deciduous, trees possess
343 traits that allow effective resource acquisition in the wet season only, whilst
344 others, obligately deciduous, species compromise this by investing in precocious
345 nutrient (and possibly carbon) acquisition which requires a more embolism-
346 resistant hydraulic system; stem or root water storage; or deep roots. In
347 summary, one explanation for the ubiquity of pre-rain green-up is that leaf
348 display is determined by biotic competitive processes, and not solely by abiotic
349 limitations.

350 **Conclusions**

- 351 • We have shown that pre-rain green-up is widespread across the region, and
352 is present in all the major vegetation types. The period between leaf out and
353 rain onset varies from 53 to 27 days in different vegetation types, and occurs
354 in vegetation types that have a wide range of mean annual rainfall and
355 interannual variability in rain onset
- 356 • Interannual variability in green-up is low, particularly in the woodlands, but
357 for a given vegetation type, spatial variation can be very high, consistent with

- 358 high levels of local adaptation, a solar radiation trigger, and resistance (if not
359 resilience) to predicted shifts in rainfall patterns
- 360 • Models of phenology will need to incorporate extra processes if they are to
361 accurately describe the observed leaf phenologies of southern Africa
362 reported here. Rainfall, and thus surface soil moisture, cannot be used to
363 explain green-up.
 - 364 • The ubiquity of pre-rain green-up can be explained by a conceptual model of
365 abiotic and biotic temporal niche separation, which may be driven by tree-
366 tree or tree-grass competition for nutrients or other resources

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375 **Author Contribution**

376 CMR developed the methods, implemented the analysis and drafted the
377 manuscript; MW, JG, EW and CERL other authors contributed to revising the
378 manuscript and developing the interpretation of the results. MW initiated the
379 study of tree phenology at the Nhambita (Mozambique) site, the results from
380 which provided the impetus for this work.

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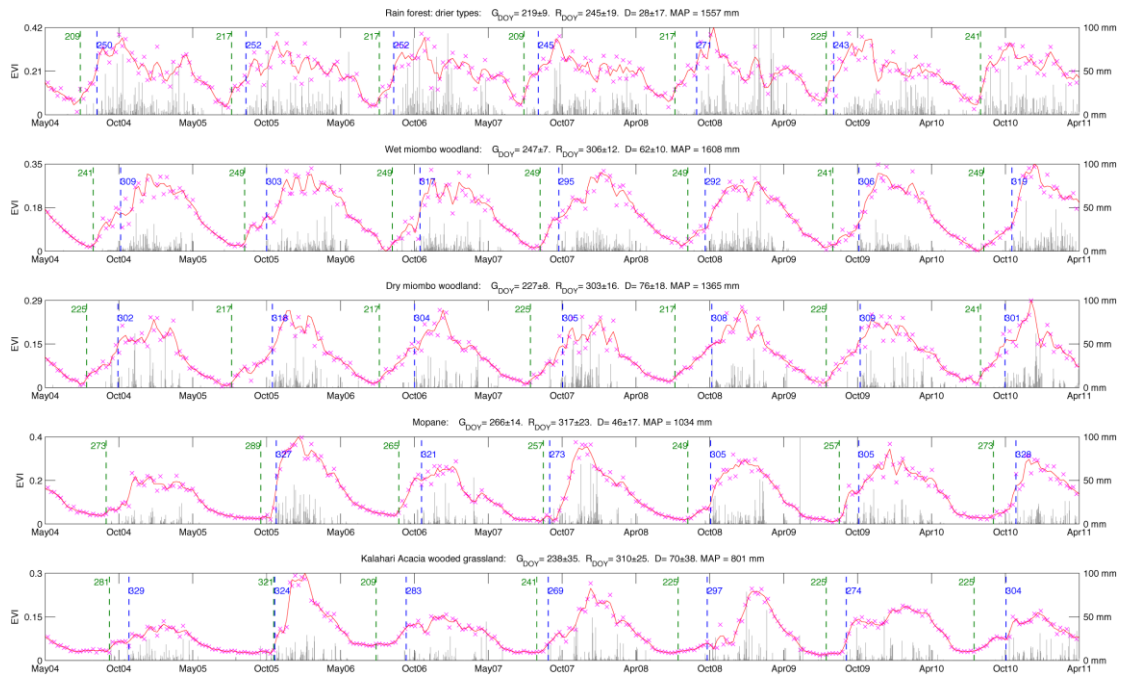
538 The following Supporting Information is available for this article:

539 Table S1 A description of the main vegetation types analysed in this study

540 **Table 1. The vegetation phenology and rainfall regime of southern tropical Africa, including its spatial and interannual variability (IAV). Day of year of green-up**
541 **(G_{DOY}) and rain onset (R_{DOY}), and the difference between them (D) are summarised for the major vegetation types of the region (based on White 1983). To look at the**
542 **relationship between IAV in G_{DOY} and IAV in R_{DOY} , the parameters of a regression for each pixel between G_{DOY} and R_{DOY} are also shown. Descriptive statistics of the**
543 **rainfall regime in each vegetation type are also included. Spatial variability is presented as the 95% interval for each vegetation type, and interannual variability is**
544 **the per pixel standard deviation (SD) of the thirteen years of data. A dry month is defined as a month with < 15 mm rain. A description of the floristics and structure**
545 **of each vegetation type is included in supplementary Table S1.**

Vegetation type [‡]	No. 0.05° pixels (1000s)	Mean day of year of green-up, G_{DOY} , days (spatial variability)	Mean IAV in G_{DOY} , days	Mean day of year of rain onset, R_{DOY} , days (spatial variability)	Mean IAV in R_{DOY} , days	Mean difference between G_{DOY} and R_{DOY}	Mean annual rainfall, mm (Coefficient of Variation)	Mean no. dry months \pm SD	Mean regression slope \pm SD	Mean regression intercept \pm SD
Wet miombo woodland	47.7	245 (205-297)	11	297 (262-327)	14	53 \pm 18	1050 (21%)	4.7 \pm 0.8	0.01 \pm 0.30	243 \pm 92
Dry miombo woodland	27	276 (235-309)	18	315 (298-332)	17	39 \pm 17	904 (18%)	5.0 \pm 0.6	0.02 \pm 0.40	271 \pm 124
Lowland rain forest	23	230 (196-273)	15	268 (245-296)	15	38 \pm 15	1382 (20%)	3.1 \pm 0.7	0.06 \pm 0.64	213 \pm 176
Mopane woodland	18.6	281 (251-306)	24	316 (301-333)	19	35 \pm 15	597 (28%)	5.6 \pm 0.4	0.13 \pm 0.47	240 \pm 146
Undifferentiated woodland	14.4	273 (223-307)	21	305 (278-327)	17	33 \pm 16	724 (24%)	4.9 \pm 0.6	0.12 \pm 0.52	236 \pm 157
Kalahari <i>Acacia</i> wooded grassland	11.8	274 (244-302)	34	316 (294-342)	23	41 \pm 14	443 (33%)	5.4 \pm 0.4	0.37 \pm 0.51	160 \pm 159
East African coastal mosaic	11.4	290 (263-326)	23	323 (298-343)	21	33 \pm 17	928 (23%)	4.6 \pm 0.6	0.12 \pm 0.44	250 \pm 140
Undifferentiated woodland transition to A. bushland & wooded grassland	11.2	274 (252-296)	29	319 (303-334)	20	43 \pm 12	521 (33%)	5.7 \pm 0.3	0.20 \pm 0.47	214 \pm 150
Rain forest: drier types	10.9	238 (195-310)	23	265 (239-288)	13	27 \pm 25	1487 (19%)	2.9 \pm 0.6	0.16 \pm 1.33	196 \pm 363
Dry deciduous forest & grassland	8.8	263 (231-288)	19	314 (304-327)	16	51 \pm 14	651 (30%)	5.6 \pm 0.3	0.07 \pm 0.47	240 \pm 144

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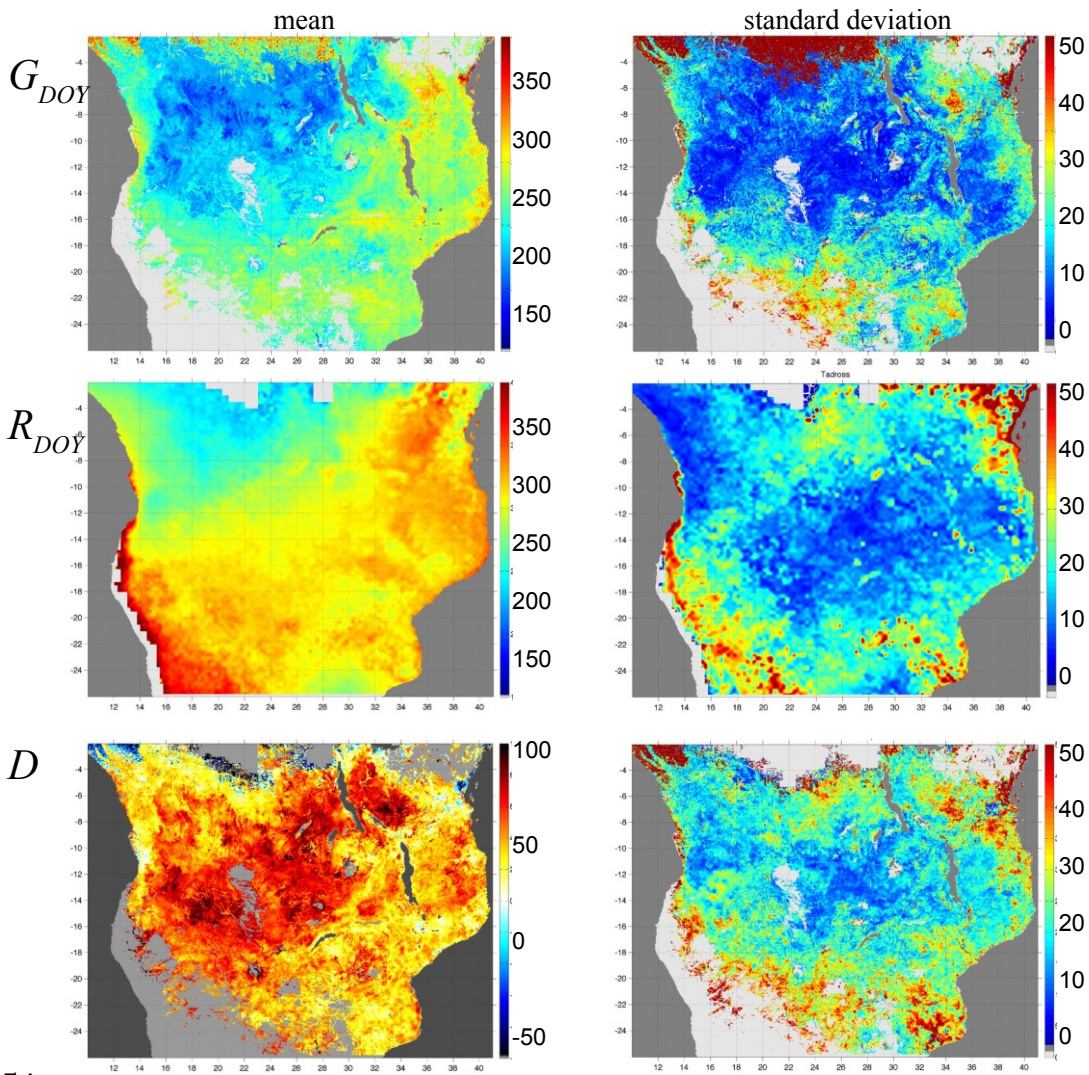
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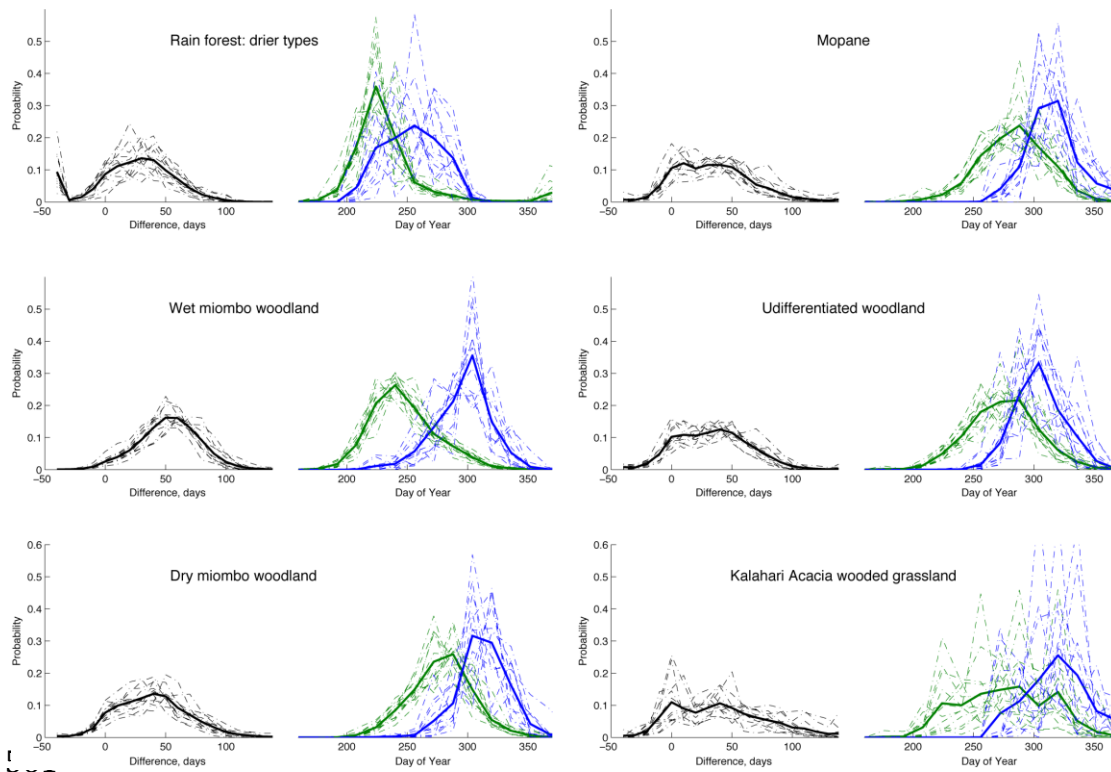
Figure 1. Examples of EVI (Enhanced Vegetation Index) and rainfall time series for randomly chosen locations in 5 major vegetation types in southern Africa. EVI data points are shown with crosses, and the smoothed fit with a pink line. Vertical lines show the day of green-up (G_{DOY} , dashed green line, green numbers) and the start of the rainy season (R_{DOY} , dashed blue line, blue numbers) as detected by our algorithms. Daily rainfall (mm) is shown with grey bars. For clarity only the middle 8 years of the time series are shown.



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555 **Figure 2. Top row: mean day of year of green-up (G_{DOY}), middle row: mean day of year of rain-**
 556 **onset (R_{DOY}), and bottom row: the difference between G_{DOY} and R_{DOY} (D). The right hand panels**
 557 **show the standard deviation of the 13 years of data, 2002-14 (inclusive). Grey areas indicate**
 558 **regions that were not included in the analysis because of very sparse or evergreen vegetation, or**
 559 **for which no green-up was detected. Grids and ticks mark 2° lat/long intervals.**

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562 **Figure 3. Probability distributions of day of year of green-up (G_{DOY} , green line) and rain onset**
 563 **(R_{DOY} , blue line), are shown on the right axes and the difference ($R_{DOY}-G_{DOY}$) on a per pixel basis**
 564 **(D , black line) on the left axes, for the major vegetation types of southern Africa. The dashed**
 565 **lines show each of the 13 years of analysis and the thicker line the mean. Frequencies are**
 566 **calculated for 16 day bins and are for pixels at their original resolution.**