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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	٠	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 dry tropics, phenological data are sparse and the processes controlling leaf 48 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

(Borchert, 1994), but these mechanisms require substantial investments in
hydraulic architecture and therefore confer large construction and maintenance
costs. Furthermore, utilising deep water at the height of the dry season requires
a costly, embolism-resistant hydraulic system (Eamus, 1999). Most seasonally
dry ecosystems are highly flammable in the late dry season, presenting an
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:
- What is the leaf phenology of the major floristic assemblages in southern
 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?
- We interpret the results of the study using ecological and evolutionary
 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

- The definition and estimation of green-up dates uses the method corroborated in these ecosystems by Ryan et al. (2014). The method utilises the fact that the land surface phenology signal detected by satellite-borne sensors is closely related to the tree leaf phenology in the period before the rains. This is because before the rains, no substantial grass growth is possible (Chidumayo, 2001; Archibald & Scholes, 2007). Given this, the method looks for the first detectable increase in vegetation greenness (represented by EVI) each year. We use MODIS EVI
- 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 (GDOY) 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 GDOY 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 some point between the annual min and 10% of the annual max in over 80% of 147 pixel-years, iii) that the backwards looking moving average definition of 148 149 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, *GDOY* is indicated as occurring 161 at measurement *i*, when:

162

$p_i > \overline{p_{\iota-1\ldots \iota-4}}$

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

165This procedure was executed for each 0.05° pixel. *D*, the number of days166between green-up and rain onset, was calculated at the 0.05° resolution of the167MODIS data, with the 0.25° rainfall data (see below) interpolated using a cubic168spline.

169 Rain onset dates

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

We masked from our analysis pixels where we expect few trees to be
present, namely pixels that had more than 10% water; pixels with a maximum
EVI < 0.4; and pixels classed as wetlands, agriculture or urban in the MODIS
12C1 land cover product for 2001. Pixels with low seasonal variation in EVI
(range < 0.2) were also excluded, as evergreen systems are not amenable to the
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 > 40209 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.

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

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

226 Differences between vegetation types

Each (floristic) vegetation type had a distinctive time series of EVI, varying from

the relatively aseasonal rainforest (Fig. 1a), to the highly seasonal woodlands

- and savannas (Fig. 1b-e). The wet miombo woodlands showed a clear and
- sustained increase in EVI up to 2 months before rain onset, at which point there

- was a much more rapid increase in EVI (Fig. 1b). The drier (miombo,
- undifferentiated and mopane) woodlands had a less distinct pre-rain green-up,
- but EVI still increased before R_{DOY} ($D = 39 \pm 17, 33 \pm 16$ and 35 ± 15 respectively).
- 234 The *Acacia* savannas had by far the highest interannual variability in rain onset
- 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, *GDOY* 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 *GDOY* 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 correlated (e.g. in the wet miombo $G_{DOY} = 1.0 \text{ x } R_{DOY} - 55$, p $\ll 0.01$, r² = 0.46; 295 296 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 dystrophia 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

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

- high levels of local adaptation, a solar radiation trigger, and resistance (if not
 resilience) to predicted shifts in rainfall patterns
- 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 to363 explain green-up.
- 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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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

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 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

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









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.



562Figure 3. Probability distributions of day of year of green-up (G_{DOY} , green line) and rain onset563(R_{DOY} , blue line), are shown on the right axes and the difference (R_{DOY} - G_{DOY}) on a per pixel basis564(D, black line) on the left axes, for the major vegetation types of southern Africa. The dashed565lines show each of the 13 years of analysis and the thicker line the mean. Frequencies are566calculated for 16 day bins and are for pixels at their original resolution.