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

Short running title: The precocious phenology of southern Africa

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Summary

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

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

Introduction

The timing of leaf emergence in tree species mediates land-atmosphere mass and energy exchanges and is an important determinant of ecosystem 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 emergence are not well understood (Richardson *et al.*, 2013). Existing work documents a wide range of phenological syndromes ranging from deciduous through brevideciduous to evergreen (Williams et al., 1997; de Bie et al., 1998; Singh & Kushwaha, 2005) and a large degree of spatial, inter- and intra-specific variability (de Bie *et al.*, 1998; Shackleton, 1999; Higgins *et al.*, 2011)

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

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

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

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

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

1. What is the leaf phenology of the major floristic assemblages in southern tropical Africa and how does it vary in time and space?
2. How common in time and space is the occurrence of pre-rain green-up?
3. For each floristic assemblage, what is the interannual and spatial variability 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 savanna tree-grass coexistence (Chesson, 1985; Walker, 1987).

Methods

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

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 LPDAAC). These two MODIS products, obtained by the Terra and Aqua satellites respectively, composite daily acquisitions over 16 day periods, 8 days out of synchrony with each other. We interleave the 16 day composites to improve the temporal resolution of the time series.

Many definitions have been used to derive day of year of green-up (G_{DOY}) dates from reflectance and/or EVI data (Reed *et al.*, 1994; Zhang, 2005; Archibald & Scholes, 2007; Bachoo & Archibald, 2007; Guan *et al.*, 2014a; Buitenwerf *et al.*, 2015), with no consensus as to techniques. To help resolve this, Ryan *et al.* (2014) tested four different methods of estimating G_{DOY} from EVI data and compared them to ground-based hemispherical canopy photography at a site in the woodlands of Mozambique. This showed that when using MODIS EVI data the i) choice of G_{DOY} definition made only small differences to the estimated 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 pixel-years, iii) that the backwards looking moving average definition of Archibald & Scholes (2007) was most reliable at detecting G_{DOY} when used with EVI data, and was conservative, tending to give later green-up dates than the ground data. Thus in this study we present the results using the Archibald & Scholes (2007) definition of green-up.

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

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

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

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

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.

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

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

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

Results

Pre-rain green-up is widespread across southern tropical Africa (Fig. 1 and 2). All the major vegetation types with a strong seasonal cycle of EVI show pre-rain green-up, and the period between G_{DOY} and R_{DOY}, D, varied from a mean of 27±25 to 53±18 days for the major vegetation types (Table 1). The number of days by which green-up preceded rain onset on average (D), was > 0 days for 78% of the terrestrial study area; > 20 days for 70% of the study area; and > 40 days for 42% of the study area. 19% of the study area was masked, mainly because of low EVI (9%) or low interannual variation in EVI (5%), anthropic land cover (3%). R_{DOY} could not be detected in >8 years (of 13) in 2% of the 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 R_{DOY} from around DOY 250. Standard deviation (SD) in R_{DOY} 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 (G_{DOY}) followed a broadly similar, but earlier, pattern, occurring first in Angola, the Congo basin and parts of Zambia (G_{DOY} ~ 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 R_{DOY}, G_{DOY} 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.

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±17, 33±16 and 35±15 respectively). 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 green-up of 41±14 days.

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

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

Discussion

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

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

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

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

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

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 accurately describe the observed leaf phenologies of southern Africa reported here. Rainfall, and thus surface soil moisture, cannot be used to explain green-up.
- The ubiquity of pre-rain green-up can be explained by a conceptual model of abiotic and biotic temporal niche separation, which may be driven by tree-tree or tree-grass competition for nutrients or other resources

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Author Contribution

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

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The following Supporting Information is available for this article:

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

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 (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 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 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 ±SD	Mean regression 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 *Acacia* 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

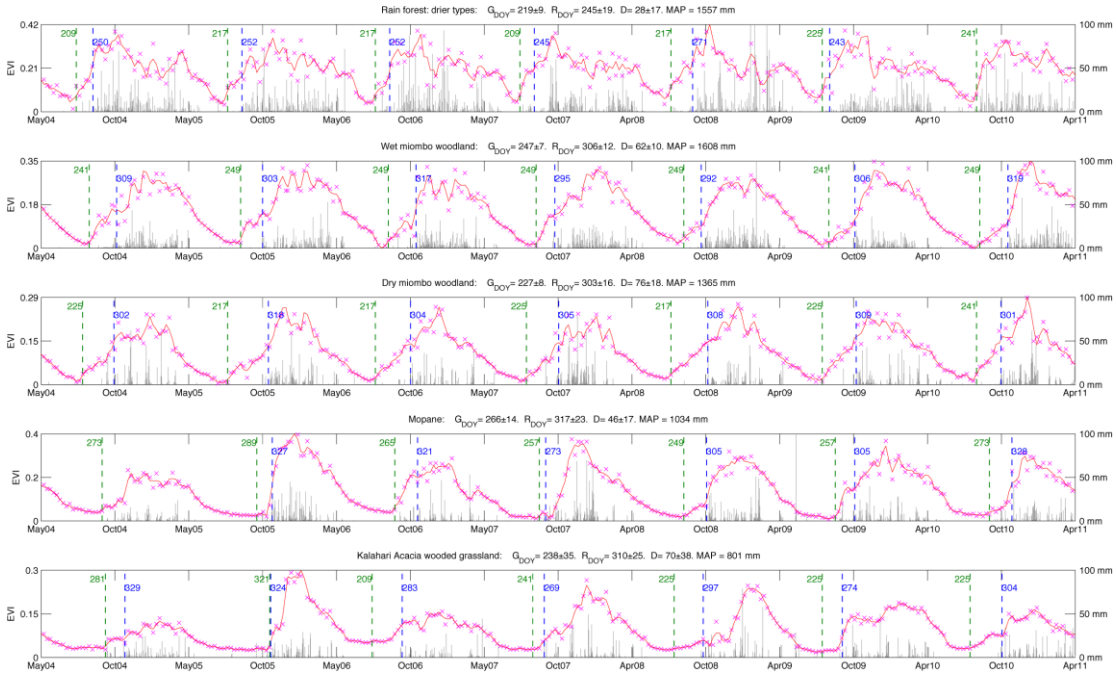

Figure 1. Examples of EVI (Enhanced Vegetation Index) and rainfall time series for randomly chosen locations in 5 major vegetation types in southern Africa. EVI data points are shown with crosses, and the smoothed fit with a pink line. Vertical lines show the day of green-up (*G_{DOY}*, dashed green 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.

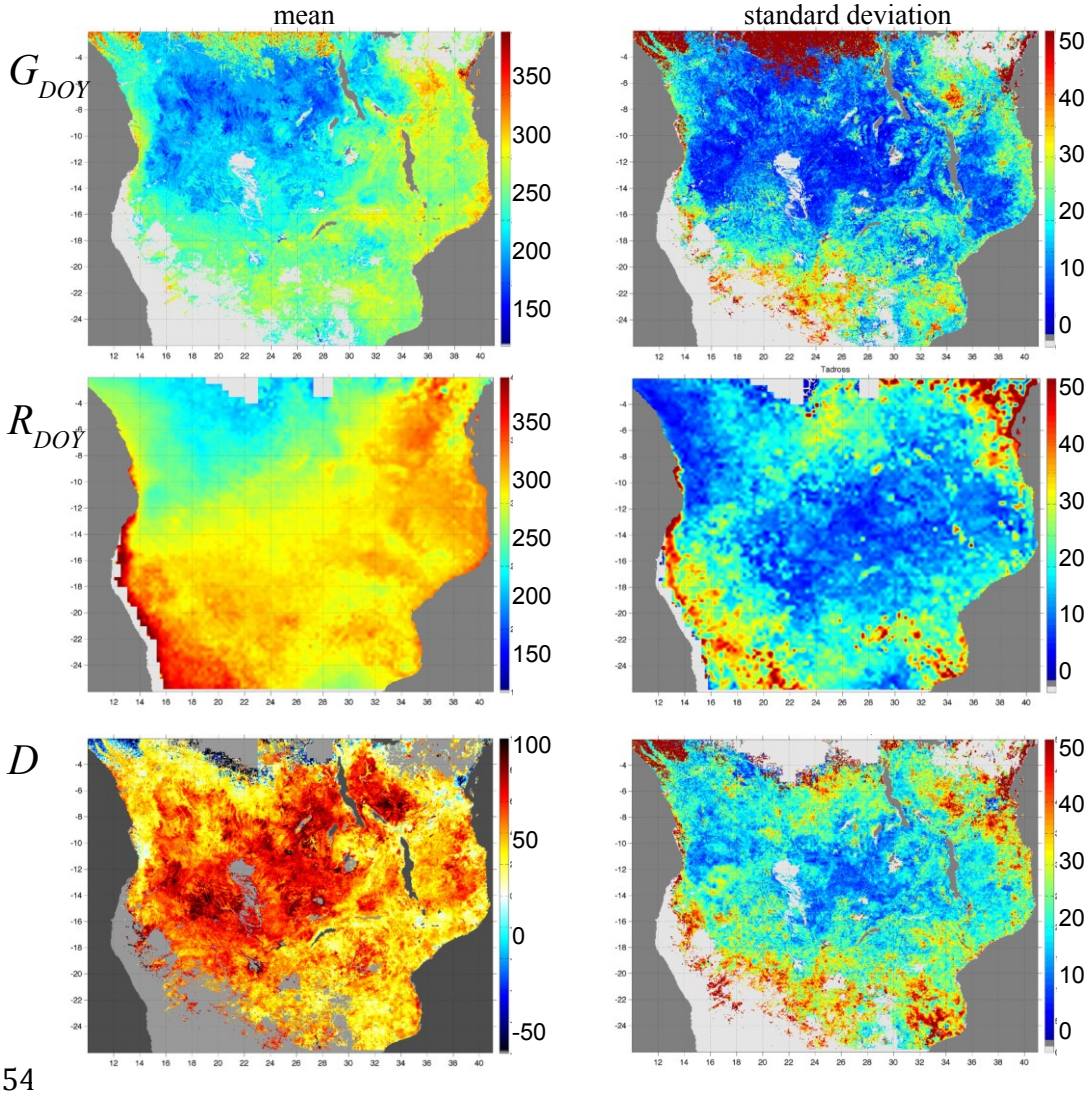

Figure 2. Top row: mean day of year of green-up (G_{DOY}), middle row: mean day of year of rain-onset (R_{DOY}), and bottom row: the difference between G_{DOY} and R_{DOY} (D). The right hand panels show the standard deviation of the 13 years of data, 2002-14 (inclusive). Grey areas indicate regions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

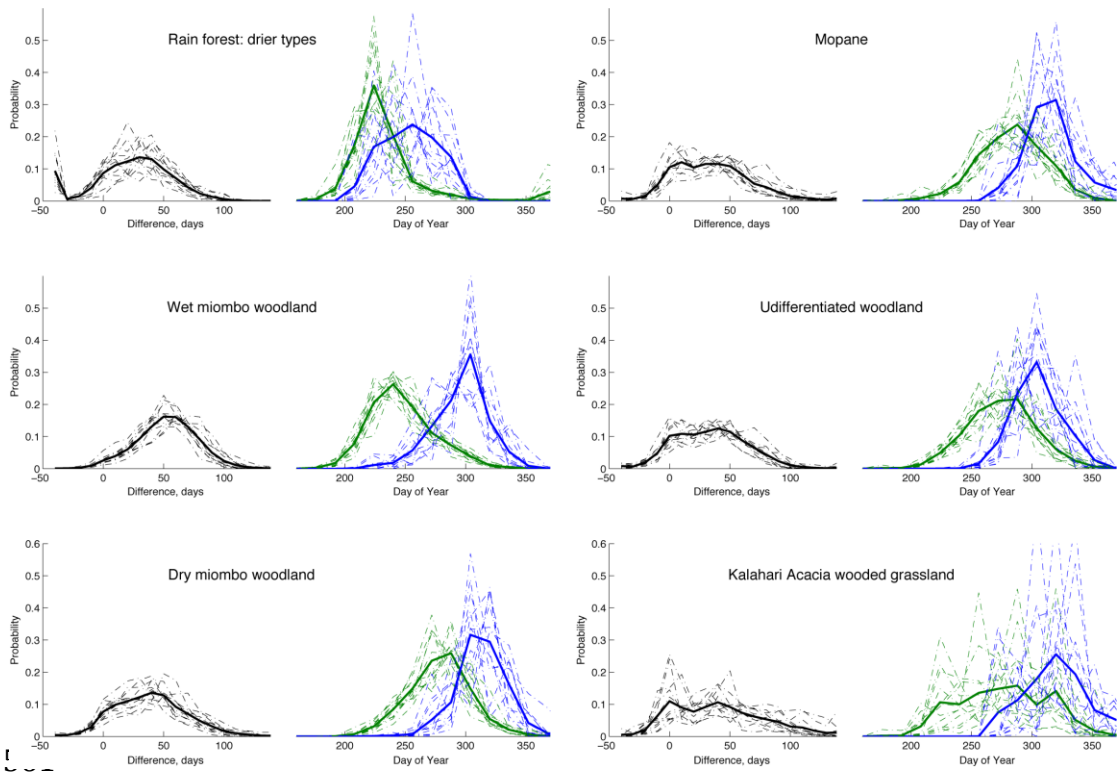

Figure 3. Probability distributions of day of year of green-up (G_{DOY}, green line) and rain onset (R_{DOY}, blue line), are shown on the right axes and the difference (R_{DOY}-G_{DOY}) on a per pixel basis (D, black line) on the left axes, for the major vegetation types of southern Africa. The dashed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