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1 **Coupling of ecosystem-scale plant water storage and foliar phenology observed by satellite**

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17 **Introductory paragraph**

18 Plant water storage is fundamental to the functioning of terrestrial ecosystems by participating in plant metabolism,
19 nutrient and carbohydrates transport, and maintenance of the plant hydraulic system’s integrity. However, global
20 observations of the size and dynamics of the water pools stored in plant tissues do not exist. Here we reveal the
21 global patterns of seasonal variations in ecosystem-scale plant water storage and their relationship with foliar
22 phenology, based on the novel space-borne measurements of L-band vegetation optical depth (L-VOD). We find
23 that seasonal variation in plant water storage is highly synchronous with foliar phenology for the boreal and
24 temperate forests, but asynchronous with a time lag of up to 180 days for the tropical dry woodlands. Contrasting
25 patterns of the time lag between plant water storage and terrestrial groundwater storage anomaly are also presented
26 amongst these ecosystems. Comparison of the water-cycle components in seasonally-dry tropical woodlands
27 suggests a buffering effect of plant water storage on the seasonal dynamics of water supply and demand. Our
28 results offer new insights into ecosystem-scale plant water relations globally and provide a basis for an improved
29 parameterization of process-based eco-hydrological and earth system modelling.

30

Water stored in plant tissues participates in the physiological and biochemical processes (e.g. metabolism and nutrient/sugar transport) and sustains the integrity of the plant hydraulic system through buffering the imbalance between transpirational water loss and root-soil water uptake^{1,2}. Water movement in plants is a passive process, following a gradient of water potential (from higher to lower) generated by transpirational demand (regulated by stomata)³ and different solute concentrations between cells (osmosis)⁴. In response to changes in environmental conditions and metabolic activities, plant water storage varies from diurnal to seasonal timescales as a function of plant structure and hydraulic strategies⁵⁻⁷. Studies on the dynamics of plant water storage typically use measurements of sap flow hysteresis and leaf water potential on individual trees over relatively limited periods⁷⁻¹⁰. Scaling up tree-level data to the ecosystem scale is challenging due to the high spatial heterogeneity of plant composition and soil properties, thus precluding large-scale (continental or global) estimates of the dynamics of plant water storage.

Satellite passive microwave radiometers sense the natural earth surface thermal emission at wavelengths of 0.1-30 cm from both the soil and vegetation layers, quantified as brightness temperature. The vegetation layer is semi-transparent, attenuating the microwave radiations passing through and creating a vegetation optical depth (VOD) proportionally linked to the vegetation water content (kg/m^2)^{11,12}. The higher the microwave frequency, the stronger the vegetation attenuation effect. The low frequency L-band (1.4 GHz) VOD (L-VOD) can detect changes in plant water storage even for dense forest canopies¹³⁻¹⁵, where the woody tissues of stems and branches hold the majority of the plant water¹⁶. This detection was not possible from VOD products at higher frequencies (>6 GHz), because their signals were dominated by the water status of canopy leaves^{13,14,17-19}. Satellite-based VOD retrievals from X-band (10.7 GHz) observations over day-time and night-time have recently been used to map ecosystem-scale anisohydricity, an indicator of stomatal and xylem regulation^{20,21}. Since 2010, the first satellite-based L-band radiometer carried by the Soil Moisture and Ocean Salinity (SMOS) mission²² further enables global scale monitoring of the dynamics in forest plant capacitive water storage, which is another key functional trait in ecohydrological processes.

Here, we used the SMOS L-VOD product^{23,24} as a proxy for time and space variations in ecosystem-scale plant water storage and examined its seasonal dynamics globally over the period 2011-2016. Since leaf area scales the

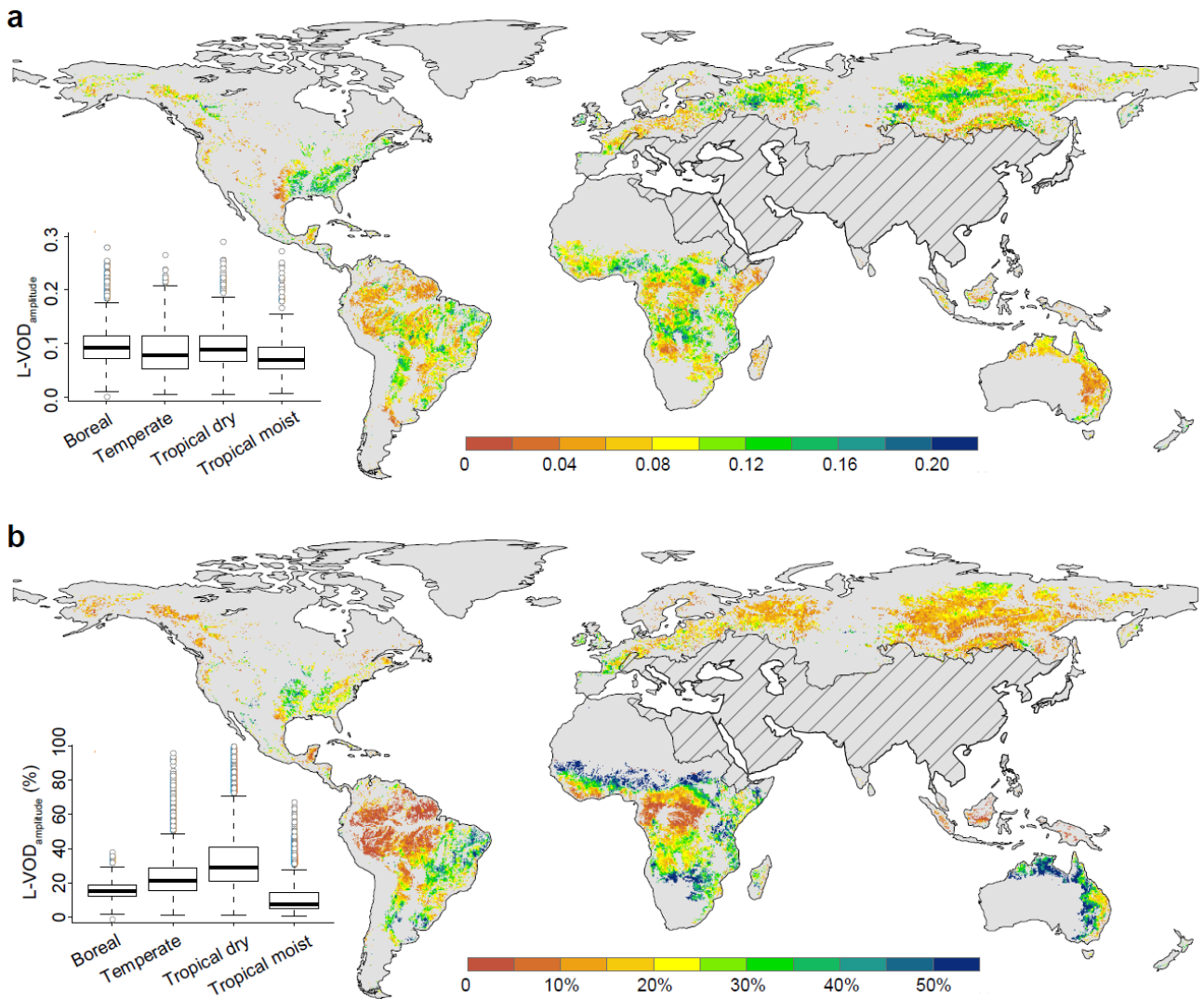
transpirational flux and photosynthetic productivity, we also examined the coupling between seasonal variations in L-VOD and foliar phenology (defined as the seasonality of satellite observed Leaf Area Index; LAI).

Results and discussion

Seasonal amplitude of L-VOD

We analysed the seasonal dynamics of ecosystem-scale plant water storage by concatenating six-year (2011-2016) SMOS L-VOD data into a mean yearly daily time series at a spatial resolution of 0.25° (Methods; Extended Data Fig. 1). Large land regions had substantial data gaps due to the influence of radio frequency interference (RFI) on the SMOS signal²⁵ (mainly in Asia; Extended Data Fig. 2), open water bodies, and lack of data retrievals from frozen soil in the northern latitudes during the cold season. We therefore restricted our analysis to pixels with continuous L-VOD data over 120 days and focused on four regions representing various biomes of contrasting ecosystem functioning: boreal, temperate, tropical dry, and tropical moist, based on a map of terrestrial ecoregions²⁶ (Extended Data Fig. 3). To ensure a high accuracy of the L-VOD seasonal patterns, we excluded areas with sparse vegetation cover where the tree cover fraction is below 5%²⁷ (Extended Data Fig. 4) and areas that were seasonally inundated²⁸, i.e. >5% area covered by flooding within an L-VOD pixel (Extended Data Fig. 5).

Globally, the annual maximum L-VOD was highly correlated with the distribution of tree cover fraction and tree height (Extended Data Fig. 6)^{29,30}. The absolute peak-to-peak seasonal amplitude of the mean L-VOD time series was similar (within 0.3 L-VOD units) amongst the four regions (Fig. 1a), even though plant productivity in these regions is limited by different climatic variables (e.g. temperature, water and radiation) and by different nutrient availability. The L-VOD seasonal amplitude *relative* to the annual maxima, however, differed significantly amongst regions (Fig. 1b), and were largest in the tropical dry region (>30% on average) and smallest in the tropical moist region (<10% on average), with temperate and boreal regions having intermediate values.



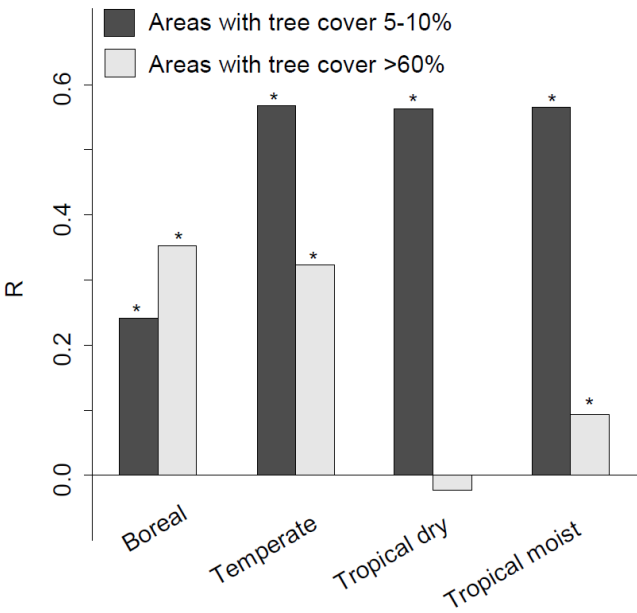
79

80 **Figure 1: Seasonal amplitude of L-VOD. a,** Absolute seasonal amplitude of L-VOD. **b,** Relative seasonal amplitude of L-
81 VOD normalized by the annual maxima. The inserted whisker plots are calculated for unfiltered pixels in four regions, i.e.
82 boreal (n = 12 880), temperate (n = 6 775), tropical dry (n = 14 152), and tropical moist (n = 7 737). Areas with substantial
83 data gaps, seasonal inundation, or eco-regions not considered in this study were filtered out and are shown in grey (see
84 Extended Data Figures 2-5). Areas influenced by RFI are marked with hatching.

85 *Seasonal coupling of L-VOD and LAI*

86 Water stored in plant tissues and its seasonal dynamics differ substantially across vegetation lifeforms (e.g. woody
87 vs. herbaceous plants). Herbaceous plants are usually annuals, so the seasonal amplitude of herbaceous water
88 storage is determined primarily by the amount of foliage in the growing season. In contrast, trees store the majority
89 of their water in woody tissues, with water-holding capacities varying amongst functioning tissues^{16,31}. Also,

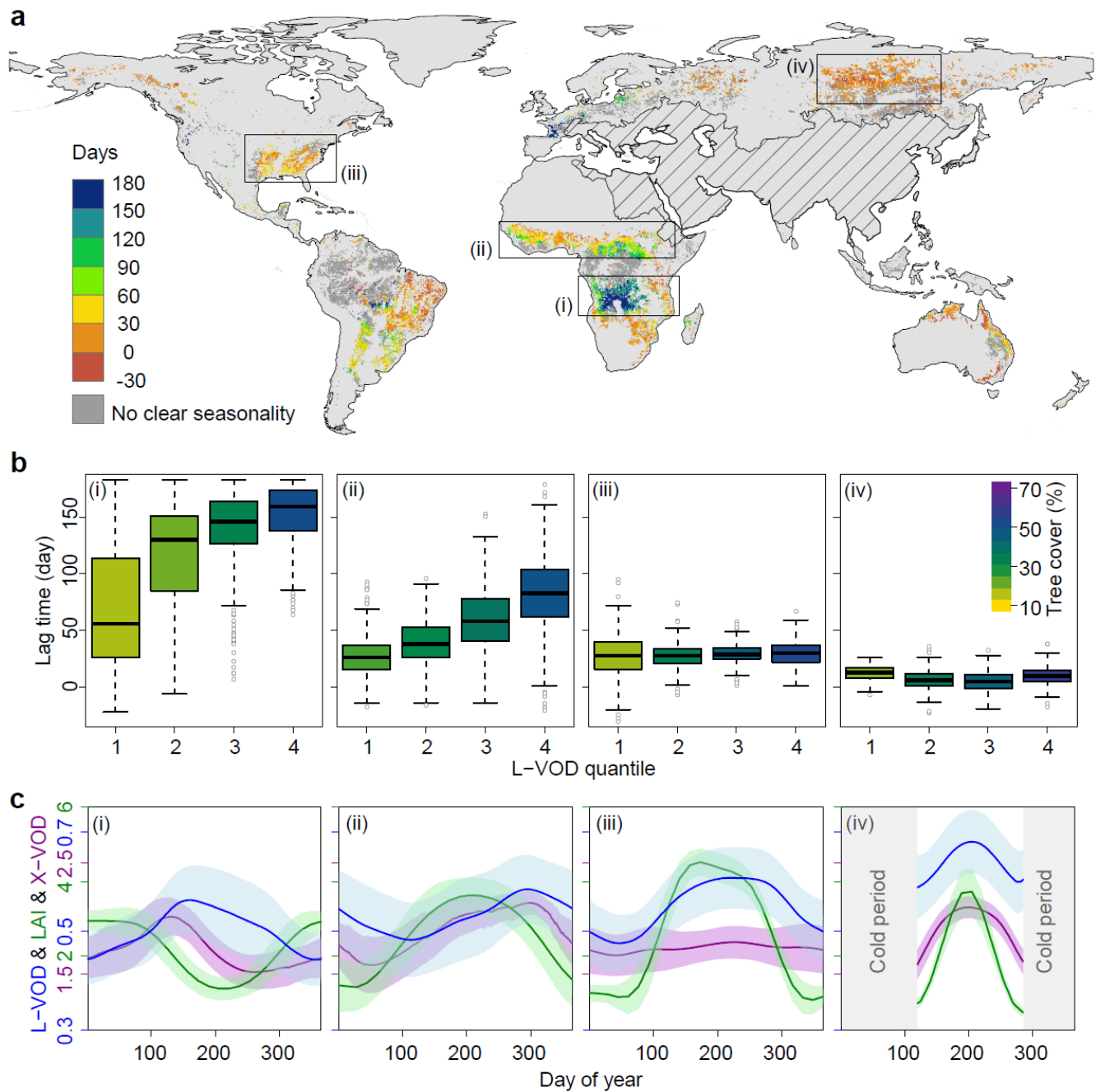
90 determining the dynamics of water storage is more complex for woody than herbaceous plants, because trees may
 91 access deep soil water and have more sophisticated hydraulic strategies³²⁻³⁴. We examined the spatial relationships
 92 between the absolute seasonal amplitudes of L-VOD and LAI in each of the four regions. As expected, linear
 93 correlations between the two signals were higher in areas with limited tree cover (5-10%) ($R \approx 0.56$, $P < 0.05$; Fig.
 94 2), except in the boreal region ($R = 0.24$, $P < 0.05$) where data gaps in winter may cause a partial loss of information
 95 in the transitional period between winter and spring/fall. The seasonal amplitudes of L-VOD, however, were
 96 positively correlated with LAI across space for areas with high tree cover (>60%) in the boreal ($R = 0.35$, $P < 0.05$)
 97 and temperate ($R = 0.32$, $P < 0.05$) regions, but the relationship was much lower in the tropical moist ($R = 0.09$, P
 98 < 0.05) region and not significant ($R = -0.02$, $P > 0.05$) in the tropical dry region. These findings suggest a lower
 99 influence of foliar fluctuations on the seasonal amplitude of plant water storage in tropical than boreal or temperate
 100 forests.



101
 102 **Figure 2: Relationship between seasonal amplitude of L-VOD and LAI.** The Pearson correlation coefficients (R) for areas
 103 with tree covers of 5-10% and >60% within the four regions: boreal ($n = 699$ and $4\,193$, respectively), temperate ($n = 1\,010$
 104 and $1\,236$, respectively), tropical dry ($n = 1\,804$ and $1\,704$, respectively), and tropical moist ($n = 237$ and $5\,493$, respectively).
 105 Significant correlations ($P < 0.05$) are labelled with asterisks. The scatterplots for each comparison are shown in Extended
 106 Data Fig. 7.

107 We then examined the seasonal synchronicity of plant water storage and foliar phenology by calculating the time
108 lag that characterizes the maximum Spearman rank correlation coefficient between L-VOD and LAI time series
109 (for pixels with a clear seasonality in both indices; see Methods). The seasonal variations in L-VOD were highly
110 synchronous with LAI in boreal and temperate regions ($R > 0.9$, $P < 0.05$), with time lags ranging from -30 to +60
111 days (Fig. 3a; positive values represent L-VOD peaks succeeding LAI). In contrast, the relationship was clearly
112 asynchronous in tropical woodlands (e.g. the woodlands around rainforests in the Congo basin), with time lags up
113 to 180 days (Fig. 3a). This time lag was found to follow a gradient in L-VOD and tree cover in two African
114 savannah and woodland regions (regions i and ii in Fig. 3a, b), but not in two other contrasted regions with wet
115 summer in southeastern USA (region iii in Fig. 3a, b) and dry summer in central Siberia (iv in Fig. 3a, b),
116 respectively. This suggests different strategies of the coupling between plant water storage and leaf phenology of
117 certain tree species in the dry tropical woodlands as compared to temperate and boreal forests.

118 The average seasonality of L-VOD and LAI are shown in Fig. 3c for pixels with equivalent tree cover fractions
119 (60-65%) from each selected region. The long L-VOD/LAI time lags in tropical woodlands caused an almost
120 reversed seasonal pattern between the two signals (Fig. 3c-i, -ii). We further included the seasonality of a high-
121 frequency X-band VOD (X-VOD)³⁵, which is more related to the water content of the upper canopy since X-band
122 microwaves penetrate less than L-band microwaves. The seasonal curves of X-VOD were between L-VOD and
123 LAI (Fig. 3c), indicating a high consistency amongst the independent satellite observations. Moreover, we
124 performed a series of sensitivity analyses on the algorithm used to retrieve L-VOD to verify the robustness of the
125 observed seasonal patterns in the tropical dry region (Fig. 3a-i; see Methods and Extended Data Figs. 8-10).

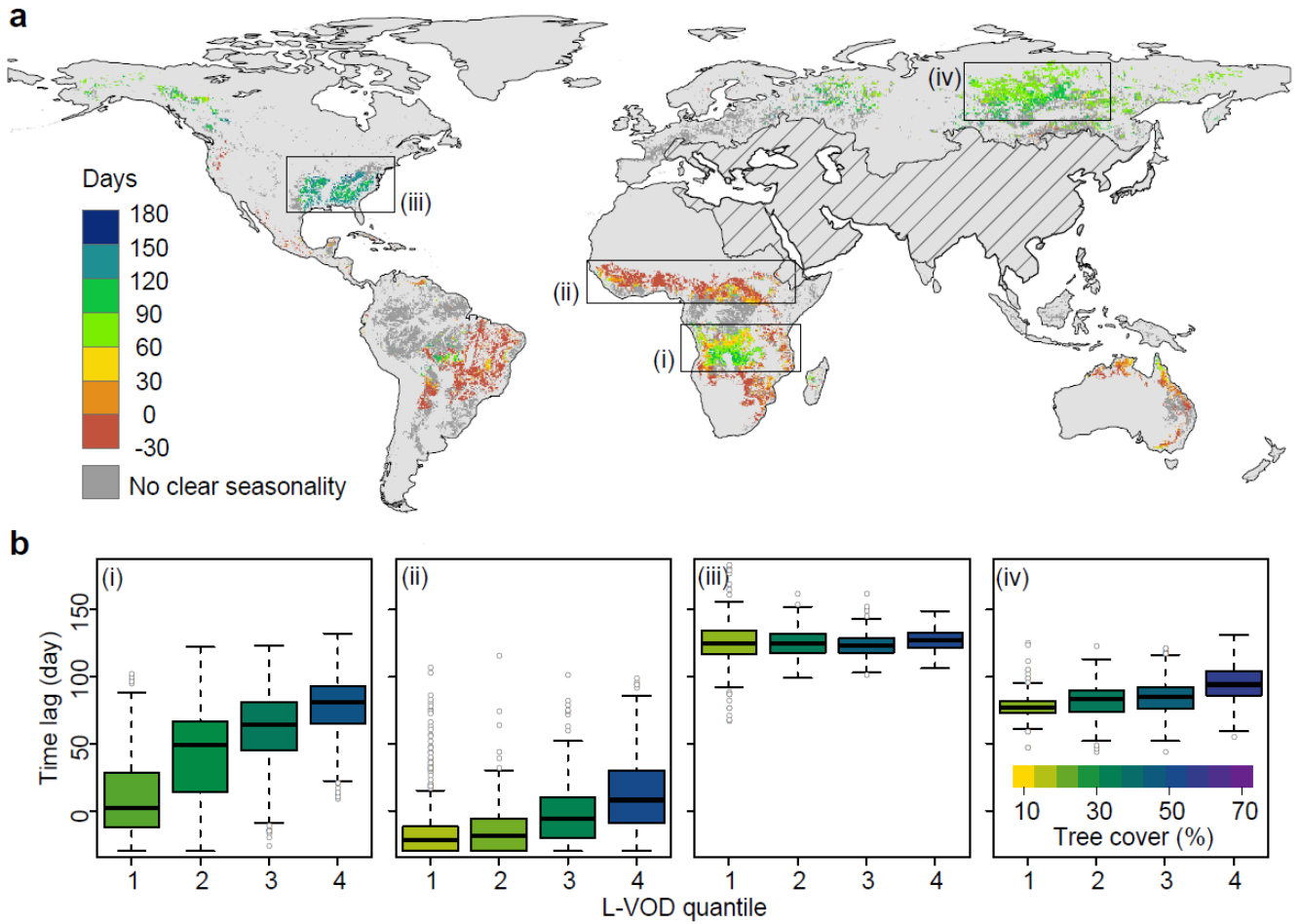


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127 **Figure 3: Temporal coupling between L-VOD and LAI seasonality.** **a**, Lag time for L-VOD to obtain the highest
 128 correlation with LAI for pixels with a clear seasonality. Areas influenced by RFI are marked with hatching. **b**, Spatial
 129 relationships between L-VOD/LAI lag time, annual maximum L-VOD, and tree cover fraction for the four selected areas
 130 indicated in **a** by black rectangles. **c**, Seasonal curves of mean L-VOD, LAI, and X-VOD for the pixels with a tree cover of
 131 60-65% for the four selected areas ($n = 152, 79, 124,$ and $212,$ respectively). The shaded curves represent the standard
 132 deviations. No VOD values were retrieved during winter periods with frozen soils.

133 *Seasonal water balance*

134 Plants regulate water exchange between sub-soil layers and the atmosphere through soil water uptake and
135 transpiration. We evaluated the role of plant water storage on the seasonal water balance at ecosystem scale by
136 analysing the development of various components of the water cycle, including plant water storage (L-VOD),
137 terrestrial groundwater storage anomaly (TWS), surface soil moisture (SM), rainfall, and estimates of transpiration.
138 The TWS integrates the ground water from the soil surface to deep ground³⁶. Seasonal variations in TWS indicate
139 the net balance between soil water replenishment (e.g., by rainfall) and consumption (e.g., by
140 evapotranspiration)³⁷. We calculated the seasonal time lag between L-VOD and TWS as it was done for L-VOD
141 and LAI. Large time lags of about 120 and 90 days were obtained in the entire regions of southeastern US and
142 central Siberia, respectively (Fig. 4). By contrast, a time lag varying from 0 to around 90 days was found in the
143 central south African savannah/woodland region (the Miombo region), following the gradient of vegetation density
144 (L-VOD and tree cover; Fig. 4) thus suggesting the unique role of certain tree species in the eco-hydrological
145 processes as compare to the herbaceous vegetation.

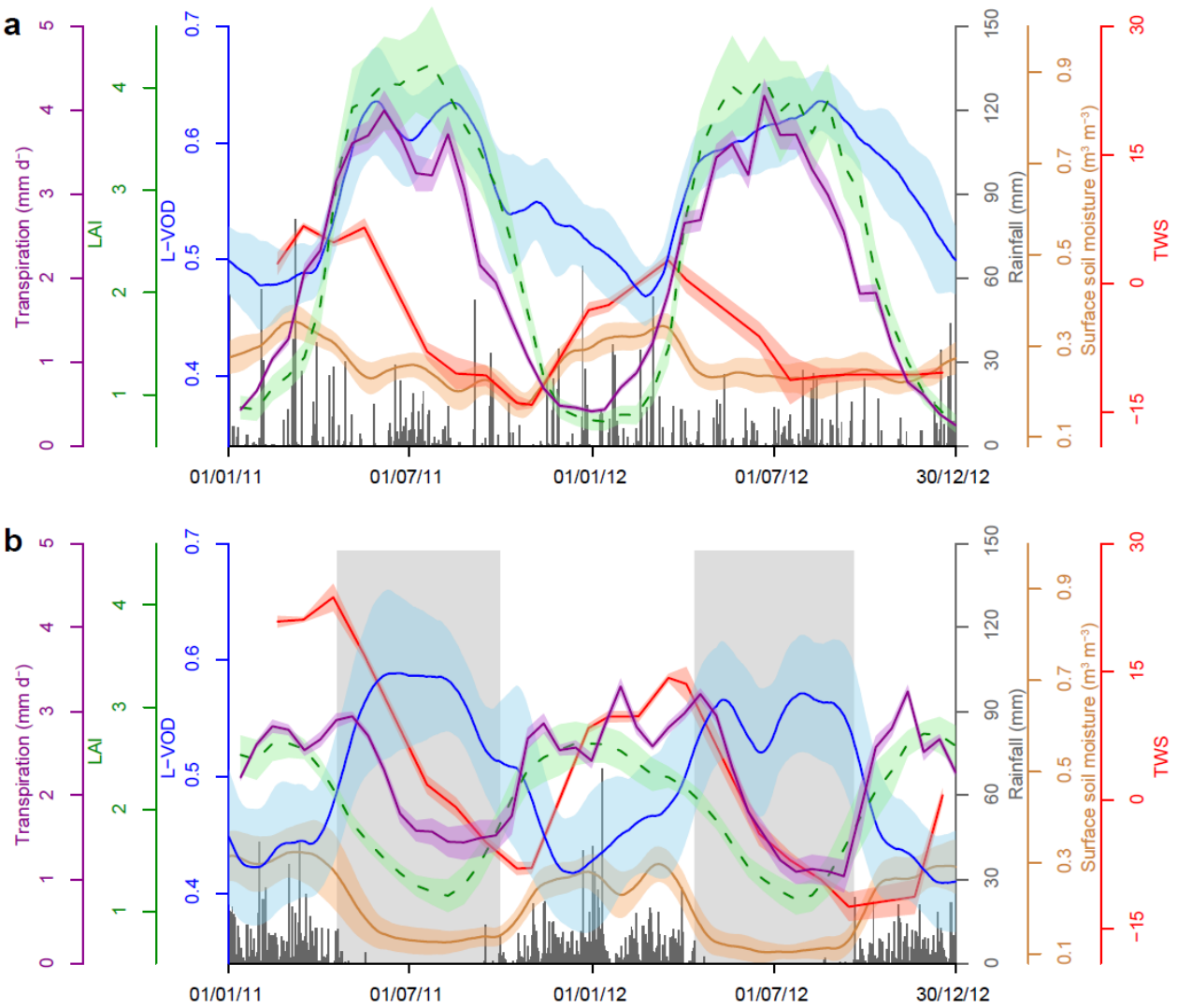


146

147 **Figure 4: Temporal coupling between L-VOD and TWS seasonality. a,** Lag time for L-VOD to obtain the highest
 148 correlation with TWS for pixels with a clear seasonality. Areas influenced by RFI are marked with hatching. **b,** Spatial
 149 relationships between L-VOD/TWS lag time, annual maximum L-VOD, and tree cover fraction for the four selected areas
 150 indicated by black rectangles.

151 To better illustrate the seasonal variation in relevant water cycle components, we studied two sites with a $1^{\circ} \times 1^{\circ}$
 152 spatial extent (16 L-VOD pixels) in the period 2011-2012 (Fig. 5): one in the US temperate forests (region iii of
 153 Figs. 3-4, centred at 33.5°N , 85.5°W) and one in the African Miombo woodlands (region i of Figs. 3-4, centred at
 154 11.5°S , 18.5°E). For the US temperate forests, rainfall and SM were relatively homogenous throughout the year,
 155 whereas TWS exhibited clear seasonal fluctuations. TWS reached the lowest level by the end of growing season,
 156 then increased and peaked around the start of growing season, followed by a continuous decrease during the
 157 growing season (Fig. 5a). Given the equalized water replenishment from rainfall over time, the seasonal
 158 fluctuations in TWS are likely attributable to the changes in transpiration. L-VOD was found to highly co-vary

159 with LAI and transpiration rate, which for the forests areas, may be explained by the requirements of abundant
 160 stem water storage to buffer the xylem tension induced by transpiration³⁸.



161
 162 **Figure 5: Seasonal water balance in two contrasting ecosystems.** The time series (2011-2012) of plant water storage (L-
 163 VOD), terrestrial groundwater storage anomaly (TWS), surface soil moisture, rainfall, transpiration, and foliar phenology
 164 (LAI) for a 1°×1° area in the (a) southeastern US temperate forests (centred at 33.5°N, 85.5°W) and (b) African tropical
 165 Miombo woodlands (centred at 11.5°S, 18.5°E). The coloured shaded curves represent the standard deviations (n = 16 for all
 166 except TWS where n = 3). The grey shaded rectangles in (b) indicate the dry seasons.

167 In comparison, the Miombo woodlands have distinct dry and rainy seasons (Fig. 5b). LAI began to increase several
 168 weeks before the onset of the rainy season, confirming the pre-rain green-up reported by previous studies³⁹.
 169 Transpiration did not increase significantly with LAI during the pre-rain green-up period, in agreement with field

170 measurements (for the tree species *Brachystegia spiciformis*) in this region⁴⁰. SM remained at the lowest level
171 during the entire dry season with almost no rainfall, but TWS decreased continuously, suggesting that deep
172 groundwater was used by trees during the dry season⁴¹. In contrast, L-VOD increased at the beginning of the dry
173 season, peaked around the time when LAI was lowest, and then decreased when LAI increased again. During the
174 rainy season, both transpiration and SM remained high, TWS was continuously recharged, and L-VOD increased
175 during the latter part of the rainy season. These results together indicate a critical role of the stored plant water on
176 buffering the seasonal dynamics of water supply and demand in these tropical dry woodlands.

177 An endogenous whole-plant control of foliar phenology has been documented in some seasonally dry tropical tree
178 species^{42,43}, where water stored in the stems directly contributes to the foliar emergence during the pre-rain green-
179 up period^{44,45}, which may explain the decrease in L-VOD at the end of the dry season. The cambium of Miombo
180 trees mainly grows during a short period late in the rainy season^{46,47}, when L-VOD increased. The continued
181 increase in L-VOD at the end of the rainy season and at the beginning of the dry season is consistent with the
182 reduced loss of transpirational water associated with leaf shedding that enables the rehydration of stem tissues and
183 the subsequent foliar emergence^{44,46}. The Miombo woodland region was the largest hot-spot area characterized by
184 long time lags between L-VOD and LAI, but the northern African woodlands and the Brazilian Cerrado have
185 similar patterns as well (Extended Data Fig. 11).

186 The specific seasonal behaviour of various water cycle components within each region indicate the adaptation of
187 plants to local climatic conditions (e.g., seasonal variations in rainfall, temperature, and photosynthetic active
188 radiation) and abiotic conditions (e.g. soil types and soil water supply) at the ecosystem scale. The spatial
189 heterogeneity in species composition needs to be considered for further in-depth hydrological/physiological
190 interpretations on the large-footprint satellite signal because closely located tree species sharing the same
191 environmental conditions can be characterized by different hydraulic strategies, e.g., between soft wood species
192 and hard wood species⁴⁴. At the same time, different species across ecosystems may have similar hydraulic
193 mechanisms as root hydraulic lift and redistribution of deep ground water were identified in both temperate forests
194 and tropical woodlands ecosystems^{48,49}.

195 Our study provides the first observational evidence of global differences in the interaction between plant water
196 storage and foliar phenology. The satellite-based L-VOD product allows for an efficient and repeated monitoring
197 of changes in large-scale plant water storage, which is highly valuable for mapping and understanding spatial
198 differences in plant hydraulic strategies^{2,50}. Furthermore, the lag analyses between satellite-observed L-VOD and
199 LAI/TWS as well as the resulting spatial patterns in relation to vegetation density and types provide a convenient
200 way to condense patterns of plant water storage across the globe, which can be used to parameterize and test relevant
201 process-based eco-hydrological and other earth system models upon reproducing observed behaviors. With future
202 expansion of the time-series covered by L-band satellite microwave observations including also improvements of
203 the spatial coverage over RFI influenced areas²³, the L-VOD product will be a strong complementary to the VOD
204 products from higher frequencies and the greenness-/productivity-oriented optical satellite records for studying
205 ecosystem responses to climate change.

206

207 **Methods**

208 *Data sets*

209 The SMOS satellite covers the earth surface nearly daily with both ascending (6 am) and descending (6 pm)
210 overpasses since the beginning of 2010. The whole system underwent the so-called commissioning phase until
211 June 2010 when various operation modes were tested, leading to less observations in comparison to the following
212 years. Therefore, we used data during the period of 2011-2016. We selected the ascending observations as plant
213 water storage usually peaks at dawn. The SMOS-IC algorithm²³ was applied to retrieve L-VOD and SM
214 simultaneously from SMOS observations, without any external vegetation products as inputs, so the current L-
215 VOD retrievals (version 103) were independent from any other vegetation indices. Conversely to other SMOS
216 products (e.g., Level 2 and Level 3)⁵¹, no remotely sensed LAI data were used in the SMOS-IC retrieval process
217 to estimate L-VOD over heterogeneous pixels, neither SM data from ECMWF (European Centre for Medium-
218 Range Weather Forecasts) were used to estimate SM over the forest fraction in mixed pixels. The native SMOS
219 spatial resolution (3 dB footprint) varies between ~27 and ~55 km depending on the incidence angles (observations

220 at high incidence angles were filtered out in SMOS-IC). The data were originally projected in the standard EASE-
221 2 grid at a 25 km spatial resolution and we further converted it into a geographical projection at a 0.25° spatial
222 resolution.

223 The LAI data were generated from the standard MODIS Collection 6 LAI products (MOD15 and MYD15; 8-day
224 composites at a 0.05° spatial resolution) from Terra and Aqua for 2011-2016⁵². The MODIS LAI algorithm
225 accounts for sun-sensor geometry. We refined the raw LAI data into 16-day composites by averaging the cloud-
226 free observations indicated by the quality flag information to minimize the influences from environmental
227 contamination, e.g. clouds, aerosols, shadows, and poor sun-sensor geometries. All high-quality LAI data were
228 then resampled to 0.25° by averaging and linearly interpolating to a daily time step to match the spatial and
229 temporal resolutions of the L-VOD data.

230 The TWS data were from the Gravity Recovery and Climate Experiment (GRACE) satellites, which measure the
231 changes in the Earth's gravitational field that are highly correlated with changes in both surface and sub-surface
232 water storage^{53,54}. The monthly GRACE TWS products are provided in three solutions by the
233 GeoForschungsZentrum Potsdam (GFZ), the Center for Space Research at the University of Texas (CSR), and the
234 Jet Propulsion Laboratory (JPL) at a 1° spatial resolution. We used the average of the three products and the
235 associated standard deviations, as suggested by recent studies⁵⁵. Only 10 observations were available for 2011 and
236 2012 due to battery management.

237 The X-VOD data were from the land parameter data record (LPDR v2) developed by the Numerical Terradynamic
238 Simulation Group at The University of Montana³⁵. The X-VOD was retrieved from the AMSR sensors at a
239 microwave frequency of 10.7 GHz for both ascending (1.30 pm) and descending (1.30 am) overpasses at a spatial
240 resolution of 0.25° . We selected the descending X-VOD retrievals for 2011-2016. The same principle (ω - τ model)
241 was used for retrieving X-VOD from AMSR microwave observations as for the SMOS-IC L-VOD retrieval
242 algorithm, which was also independent from optical vegetation indices.

243 The data for tree cover fractions were produced by Chiba University for 2008²⁷, since this dataset outperforms the
244 MODerate-resolution Imaging Spectroradiometer (MODIS) Vegetation Continuous Fields product (MOD44B) for

245 African drylands where MOD44B largely underestimates the woody cover^{56,57}. Tree height data was from
246 spaceborne light detection and ranging (lidar) data obtained by the Geoscience Laser Altimeter System (GLAS)⁵⁸.
247 The rainfall data were from the Tropical Rainfall Measurement Mission (TRMM) 3B42 v7 daily product⁵⁹, which
248 were estimated from satellite measurements at a 0.25° spatial resolution.

249 The transpiration data were from estimates by the Global Land Evaporation Amsterdam Model (GLEAM) v3.1a,
250 which used a set of algorithms for estimating a series of water-cycle components (without plant water storage) at
251 a daily time step and 0.25° spatial resolution^{60,61}.

252 *Analysis of seasonal lag*

253 We concatenated the six-year (2011-2016) data into a mean yearly daily time series for each pixel to obtain a clear
254 and reliable seasonality in L-VOD (see an example pixel in Extended Data Fig. 1a and b). The median of raw L-
255 VOD retrievals from the same day of the year for 2011-2016 was first used to form an average seasonality. Second,
256 a 30-day moving median was determined, followed by calculating the anomalies between the raw data and the
257 median curve. The data points larger/smaller than the median curve +/- the standard deviation of the anomalies
258 were defined as outliers and thus removed from the subsequent analysis (de-noise). Finally, a 30-day moving-
259 average curve was calculated for the valid data points. The seasonality of LAI and X-VOD were determined using
260 the same method as for L-VOD.

261 For the L-VOD seasonality, we accounted for both the data noise and the actual seasonal variations in plant water
262 storage, using the ratio between the seasonal amplitude and the standard deviation of the anomalies as an indicator
263 of the intra-annual variability (Extended Data Fig. 1c). Pixels with a ratio >1.2 (a buffer of 20% standard deviation)
264 were deemed to be characterized by a clear seasonality, despite the data noise, and were thus selected for further
265 lag analysis with the LAI seasonality, and pixels with a ratio ≤ 1.2 were deemed to have no clear seasonal patterns
266 in L-VOD. Double growing seasons will introduce large uncertainties in quantifying the time lag, so we limited
267 the analysis to pixels characterized by a single growing season in both L-VOD and LAI seasonality. We normalized
268 the mean seasonality of each pixel to 0-1 by subtracting the minimum value and then dividing by the amplitude,
269 and identified pixels with only two 0.5 crossing points as being characterized by a single growing season⁶².

270 *Sensitivity analysis on the L-VOD seasonality*

271 The SMOS-IC algorithm applies a constant soil surface roughness and effective scattering albedo over time and
272 use an effective temperature input from ECMWF estimates^{23,24}, which will introduce uncertainties in the L-VOD
273 retrievals. We performed a series of sensitivity analyses focusing on the possible influences from these uncertainty
274 settings/sources on the L-VOD seasonal pattern retrieved from the SMOS-IC algorithm over the Miombo region,
275 where L-VOD peaks during the dry season. Specifically, we applied various value settings of these input
276 parameters covering a dynamic range larger than the expected ones to examine the possible resulting changes in
277 the L-VOD seasonality.

278 Soil surface roughness may change in relation to agricultural practices, but very unlikely over natural
279 environmental conditions at the satellite footprint scale as for the Miombo region. The roughness parameter (HR)
280 used in the SMOS-IC algorithm is 0.3 for the forested pixels in the Miombo region^{63,64}. We compared the L-VOD
281 retrievals over this region by setting HR to 0.2 and 0.4, respectively, but found little difference in the seasonal
282 cycle from a setting of 0.3 used in the original SMOS-IC algorithm (Extended Data Figure 9). Because the seasonal
283 changes in soil surface roughness are expected to be much smaller than an HR range of 0.2, they will have very
284 limited influence on the observed L-VOD seasonal trends.

285 Canopy leaves have dominant effects on the emissivity and effective scattering albedo of deciduous forests at
286 higher frequencies (>6 GHz), but the leaf effects are limited at L-band as suggested by several studies which show
287 that stems and branches are the main elements contributing to forest emissivity at L-band^{13-15,63}. Therefore, in the
288 SMOS-IC algorithm, a constant effective scattering albedo (Omega) value of 0.06 was used for the Miombo
289 woodlands although dominated by a deciduous forest type with a clear annual cycle in the canopy leaf
290 conditions^{23,65,66}. To test the influence from an expected small change in the effective albedo (lower than 0.01) on
291 the retrieved L-VOD values, we ran the SMOS-IC algorithm by setting the Omega value to 0.05 and 0.07,
292 respectively over the Miombo region⁶⁷. Again, the results show little difference in the retrieved L-VOD seasonal
293 patterns between these different settings (Extended Data Figure 10). Therefore, using a constant effective
294 scattering albedo of 0.06 in the SMOS-IC algorithm will have a very limited influence on the observed L-VOD
295 seasonal trends over the Miombo woodlands.

296 The ECWMF soil and vegetation temperatures used to estimate the effective surface temperature (T_s) in the
297 SMOS-IC algorithm⁶⁸ may have a root mean square deviation as high as a few Kelvin^{69,70}. We applied a drastic
298 approach to investigate its possible impacts on the L-VOD seasonal patterns, that is, setting a constant effective
299 temperature (T_s) value over the course of the year. Two constant values (291 K and 295K) with a range of 4 K
300 were considered based on the observed average value (~293 K) and standard deviation (~2 K) of seasonal changes
301 in T_s over the Miombo region. Results were compared to L-VOD retrievals considering dynamic ECMWF
302 estimations of T_s , as applied in the SMOS-IC algorithm. Again, little difference in the retrieved L-VOD values
303 from the different T_s settings were observed (Extended Data Figure 11). This suggests a relatively small impact
304 on L-VOD seasonality from possible uncertainties in the estimates of T_s computed from ECMWF data, which
305 may be attributable to the narrow seasonal changes in temperature over the Miombo region. Therefore, the
306 uncertainties and possible erroneous trends associated with the ECMWF temperature products cannot explain the
307 specific L-VOD signatures observed in this region.

308 *Analysis of seasonal water balance*

309 A variety of water-cycle components were plotted together to investigate the water balance at a US temperate
310 forest site and a tropical Miombo woodland site. Specifically, the SMOS L-VOD and SM data were smoothed
311 using a moving-average method (window size of 30 days). Daily estimates of transpiration were aggregated to a
312 16-day mean to match the MODIS LAI temporal resolution for better visualization. The onset of the rainy season
313 (or end of the dry season) in the tropical Miombo site was determined following the criteria³⁹: (1) a total rainfall
314 of 25 mm within 10 successive days, followed by (2) a total rainfall >20 mm within 20 days. The start of the dry
315 season (or end of the rainy season) was defined as the last day with rainfall >10 mm.

316 *Data availability*

317 The SMOS L-VOD and SM products are available upon request and will be made publicly available by CATDS
318 (Centre aval de traitement des données SMOS). MODIS LAI data are available from <http://sites.bu.edu/cliveg>.
319 Anomalous GRACE data for terrestrial groundwater storage are available from <https://grace.jpl.nasa.gov>. X-VOD
320 data can be downloaded from www.ntsg.umn.edu. Tree cover data are available from

321 <https://globalmaps.github.io/ptc.html>. Tree height data can be downloaded from
322 https://webmap.ornl.gov/ogc/dataset.jsp?ds_id=10023. The global inundation map is available upon request at
323 www.estellus.fr/index.php?static13/giems-d15. TRMM rainfall data are available from <https://pmm.nasa.gov>.
324 Transpiration data can be downloaded from <https://www.gleam.eu>.

325 **Code availability**

326 The code used for seasonal lag analyses in this study was deposited in GitHub:
327 <https://github.com/fengtian2017/SMOS-L-VOD-seasonality>

328

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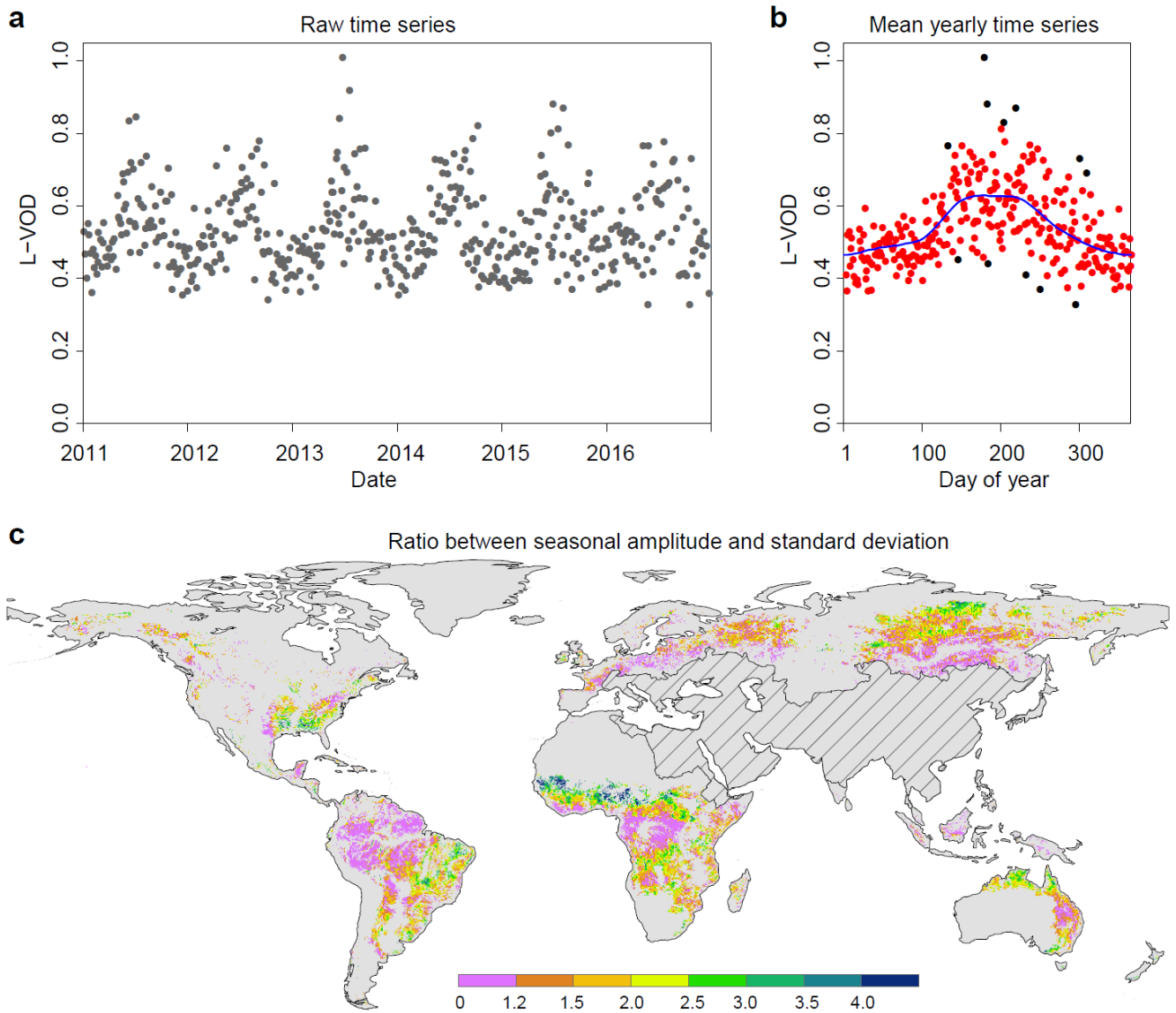
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523 **Author Contributions**

524 F.T., J.P.W., M.B., and R.F. designed the study with inputs from P.C., J.C., J.P., and A.R.. J.P.W., Y.K., A.M.,
525 N.R-F., and A.A.Y. prepared the SMOS-IC data and performed the sensitivity analyses. C.C. and R.B.M. prepared
526 the MODIS LAI data. F.T. performed data analyses. The results were interpreted by J.P.W., A.R., J.C., F.T., P.C.,
527 J.P., J.O., J.C.D., X.T., N.R-F., A.M., T.T., A.A.Y. and R.F.. F.T. drafted the manuscript with editing by P.C., J.P.,
528 J.O., J.C. and contributions from all co-authors.

529 **The authors declare no competing financial interests.**

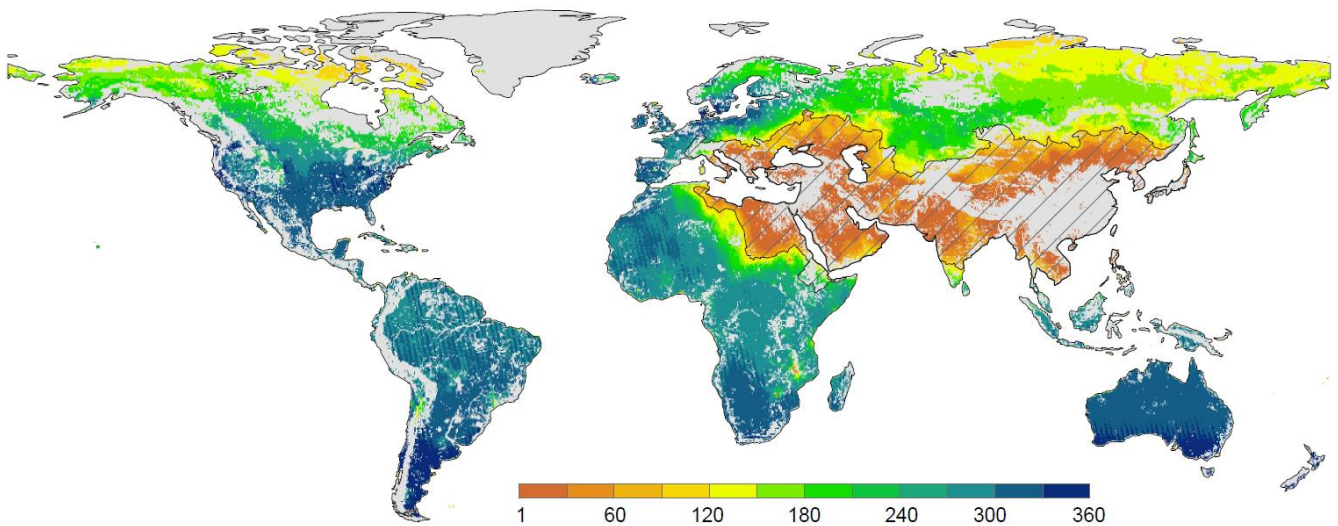
530 **Materials and correspondence** should be addressed to F.T. (feng.tian@nateko.lu.se; ftian2012@gmail.com) and
531 J.P.W. (jean-pierre.wigneron@inra.fr).



532

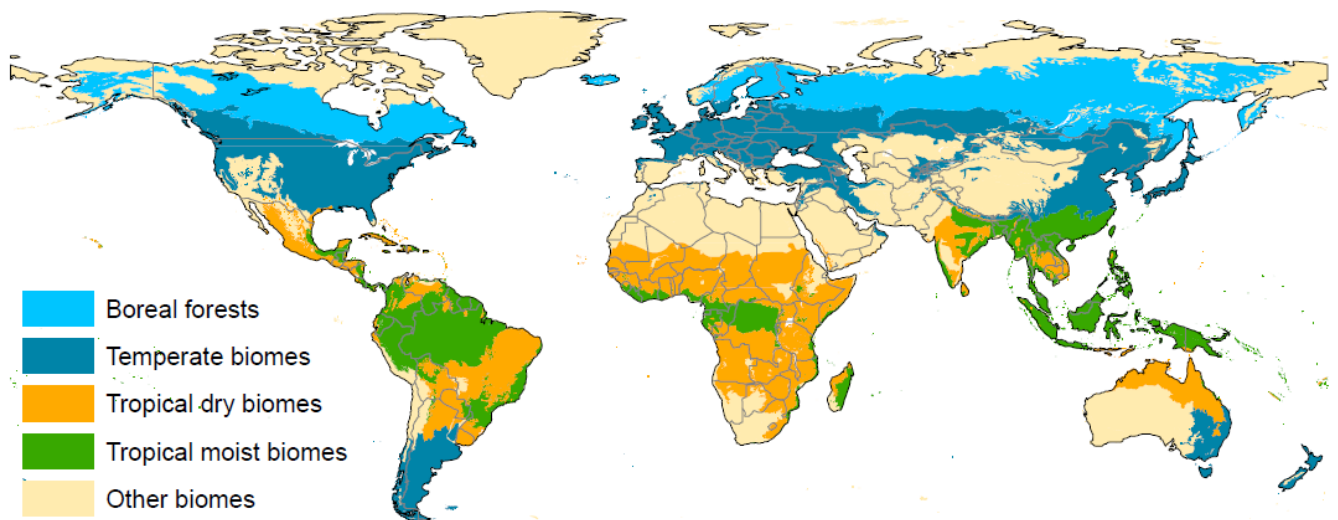
533 **Extended Data Figure 1: SMOS-IC L-VOD data processing.** **a**, The raw L-VOD time series for 2011-2016 from an
 534 example pixel (location: 11.25°S, 18.25°E). **b**, The mean L-VOD seasonality of the example pixel. The red points were
 535 selected for further smoothing and the calculation of standard deviations, and the black points were rejected as outliers. The
 536 blue curve is the moving average of the red points. **c**, Global distribution of the ratio between seasonal amplitude and standard
 537 deviation. Masked areas are explained in the text. The ratio between seasonal amplitude and standard deviation for the example
 538 pixel is 2.3.

539



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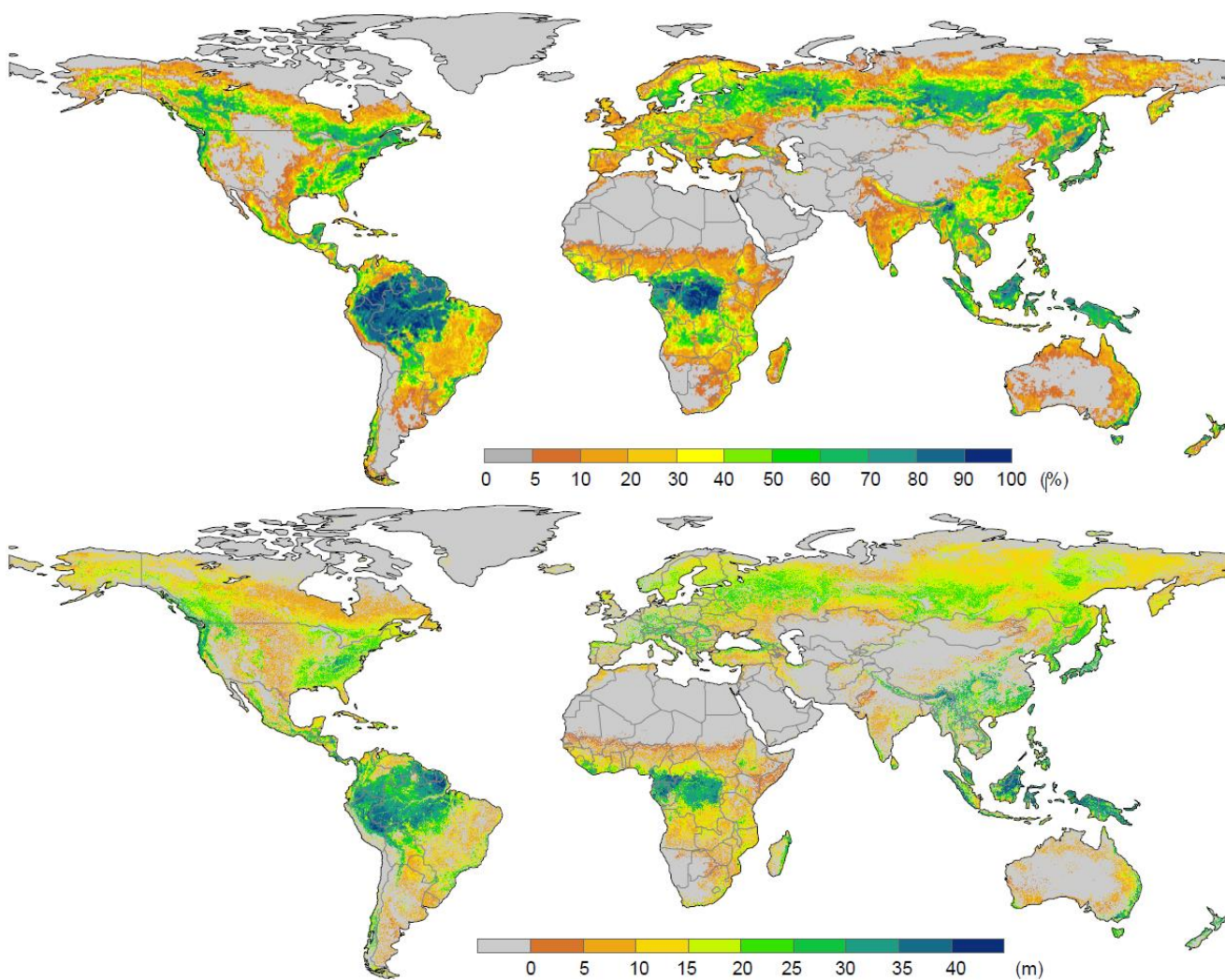
541 **Extended Data Figure 2: Available number of SMOS VOD retrievals of the mean yearly daily time series (ascending**
 542 **overpass).**



543

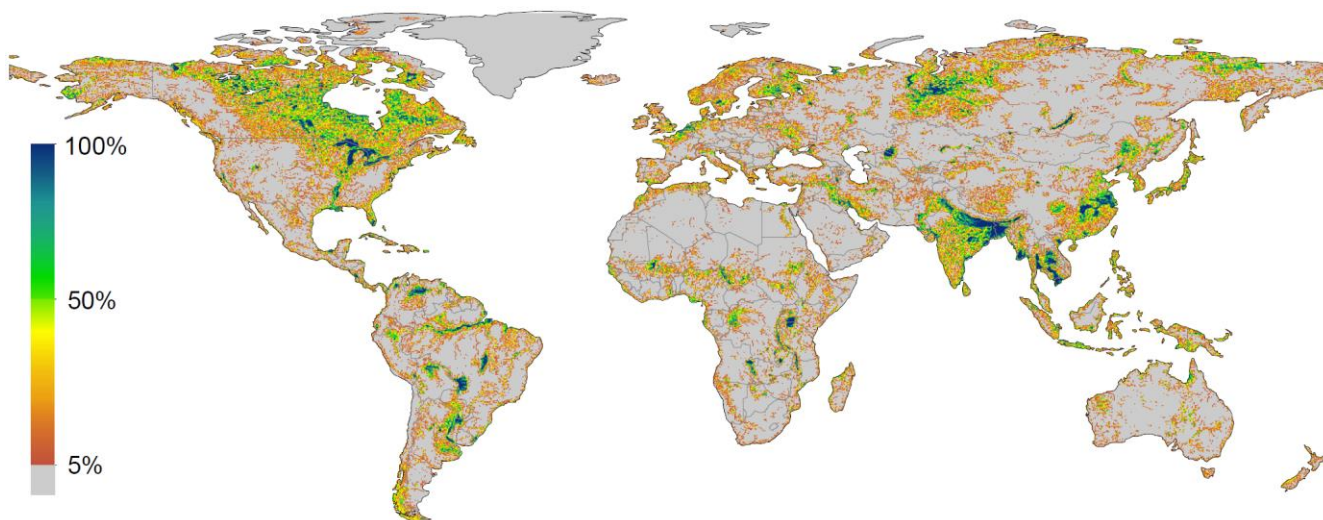
544 **Extended Data Figure 3: Spatial extent of five merged regions.** Modified from Olson, et al.²⁶. The 'Other biomes' category
 545 contains deserts & xeric shrublands, flooded grasslands and savannahs, mangroves, and was excluded from the analysis partly
 546 due to the higher uncertainties in these regions.

547



548

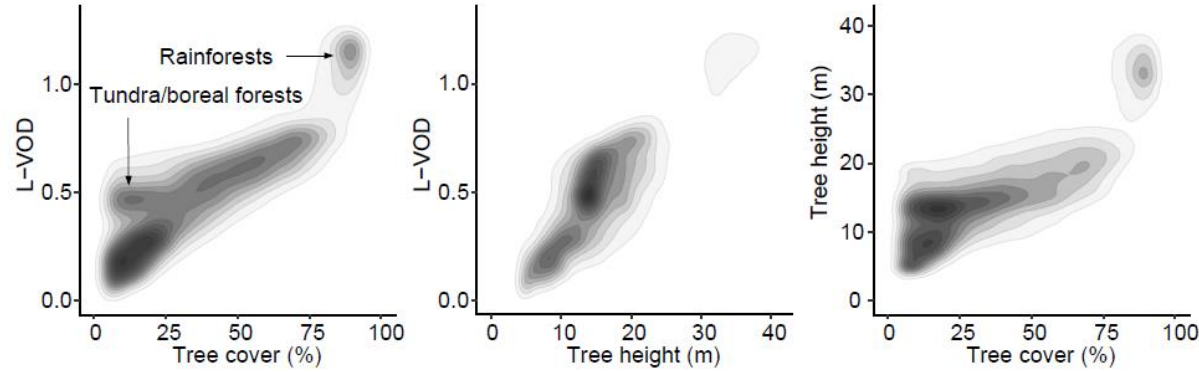
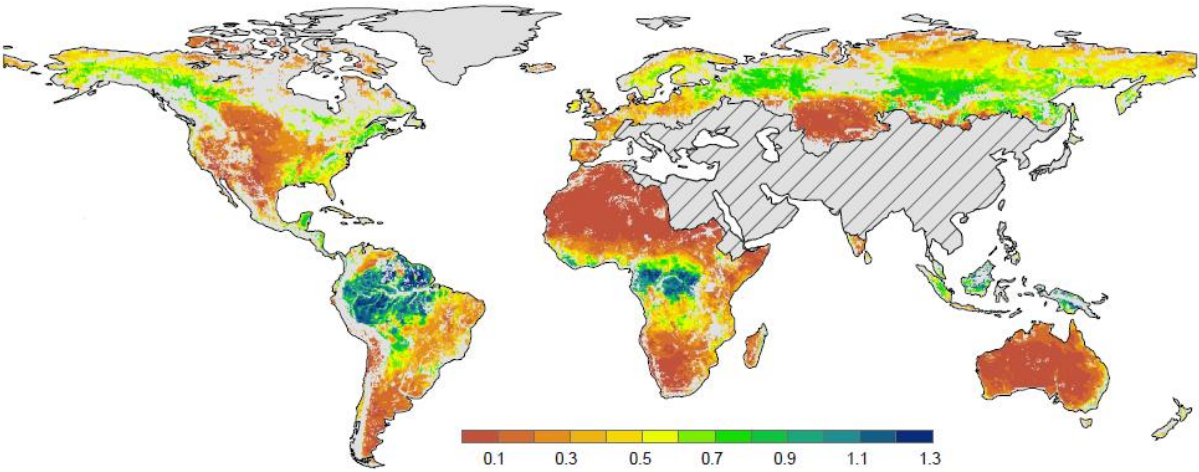
549 **Extended Data Figure 4: Global tree cover fractions²⁷ and tree height estimates⁵⁸.**



550

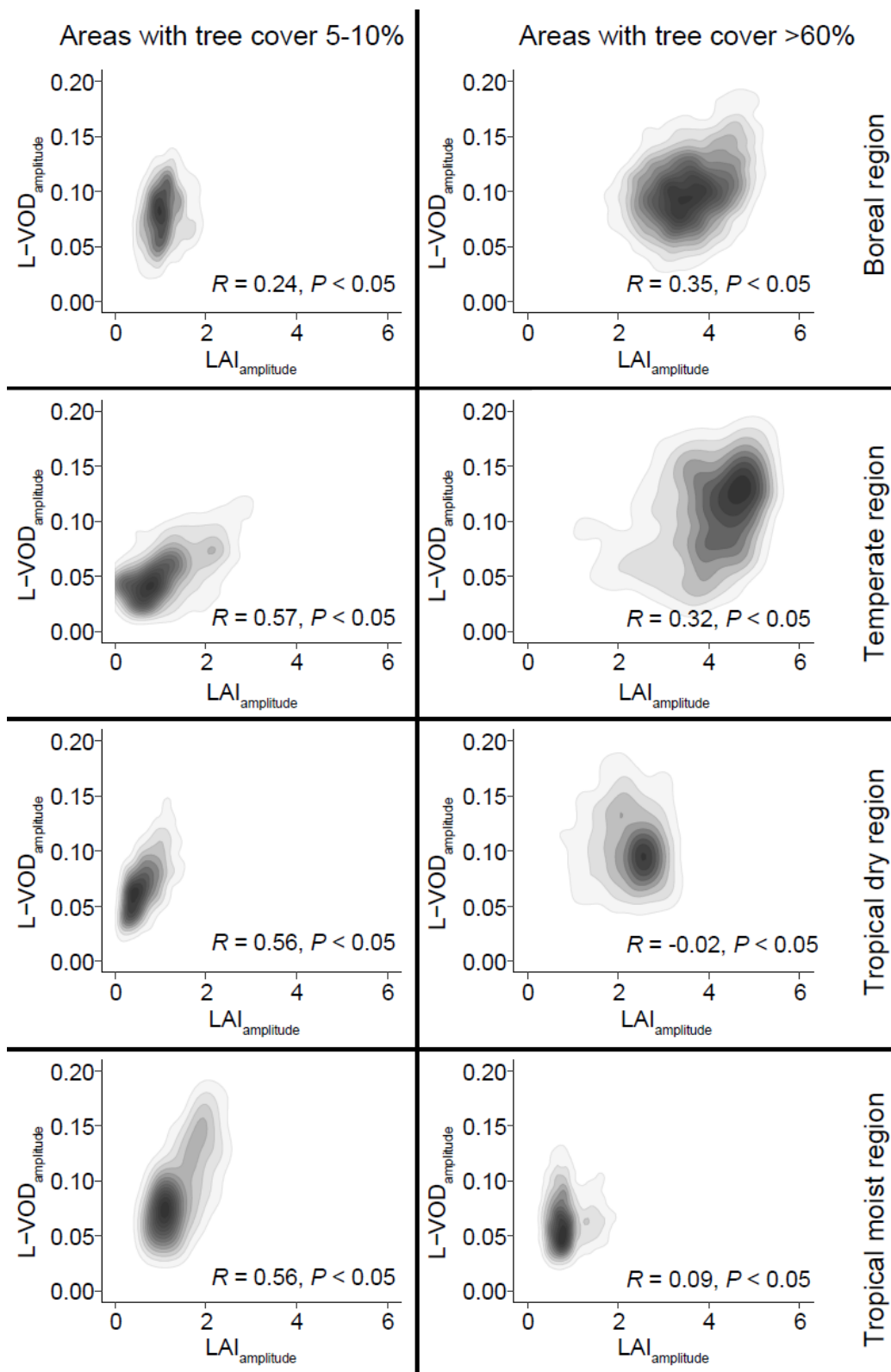
551 **Extended Data Figure 5: Global inundation map²⁸.**

552



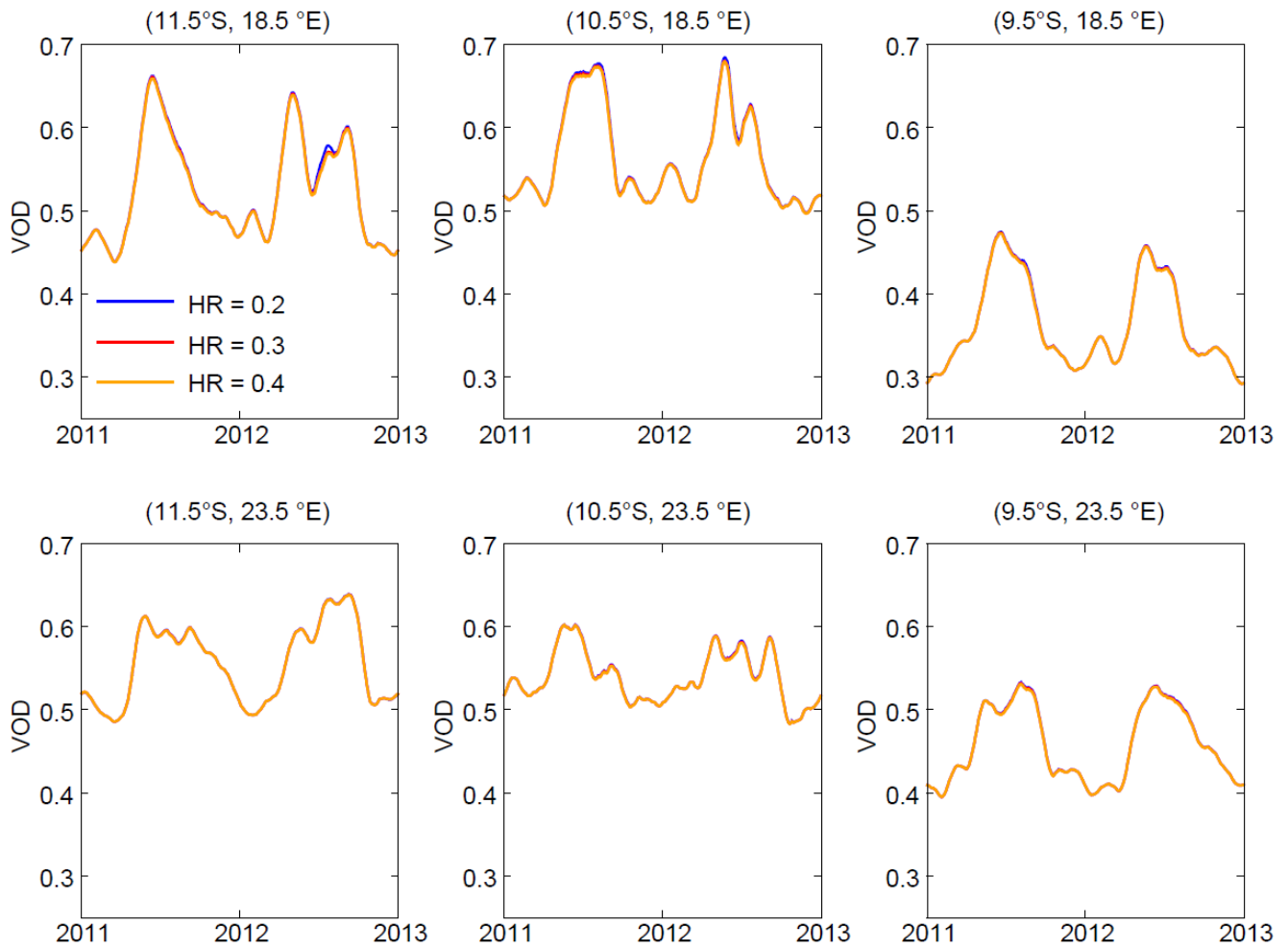
553

554 **Extended Data Figure 6: Global variability in annual maximum L-VOD and the relationships with tree cover**
555 **fraction and tree height.**



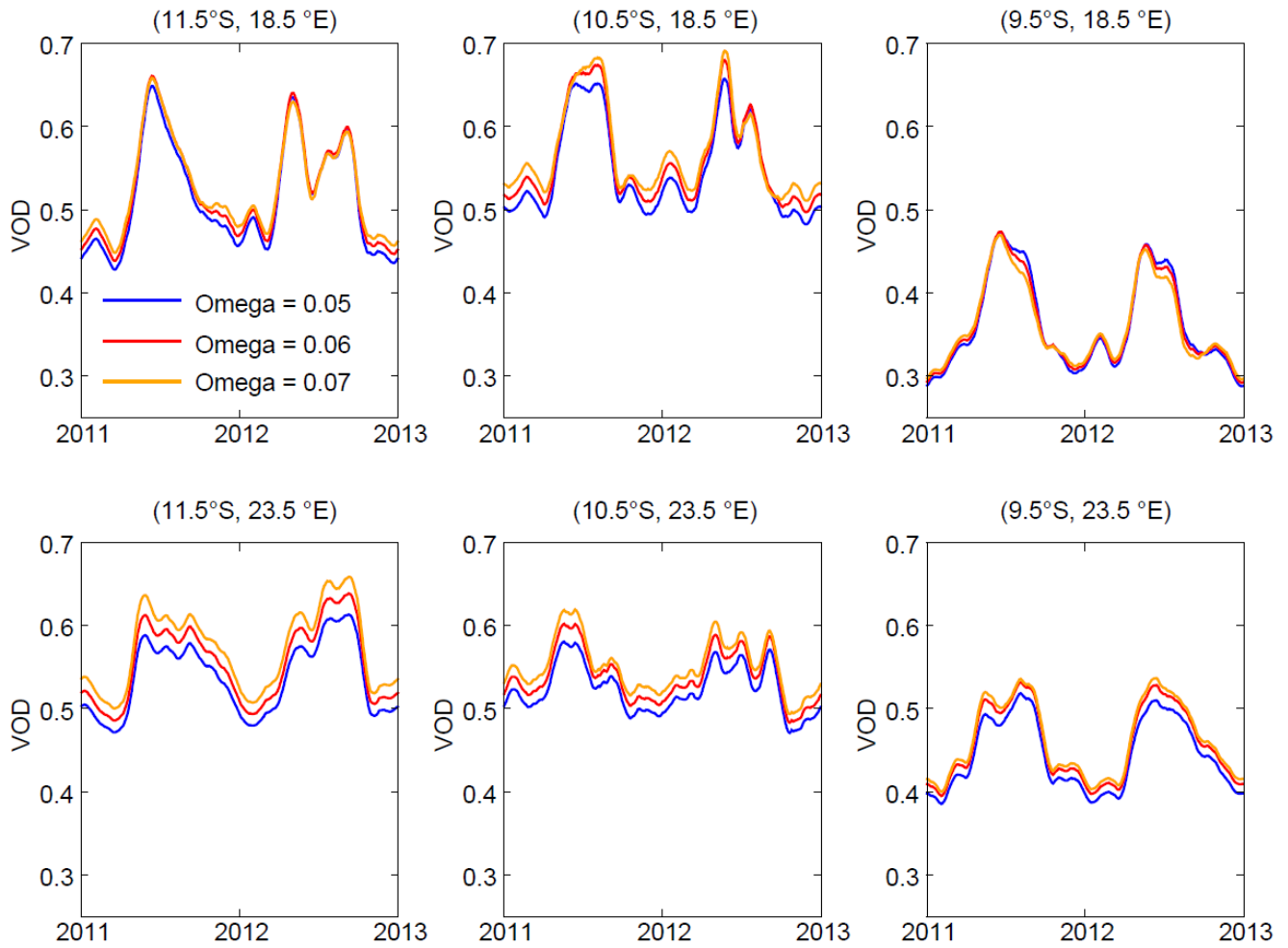
556

557 **Extended Data Figure 7: Scatterplots between seasonal amplitudes of L-VOD and LAI, grouped by areas with tree covers**
 558 **of 5-10% and >60%, respectively, within the boreal, temperate, tropical dry, and tropical moist regions. R is the Pearson**
 559 **correlation coefficient.**



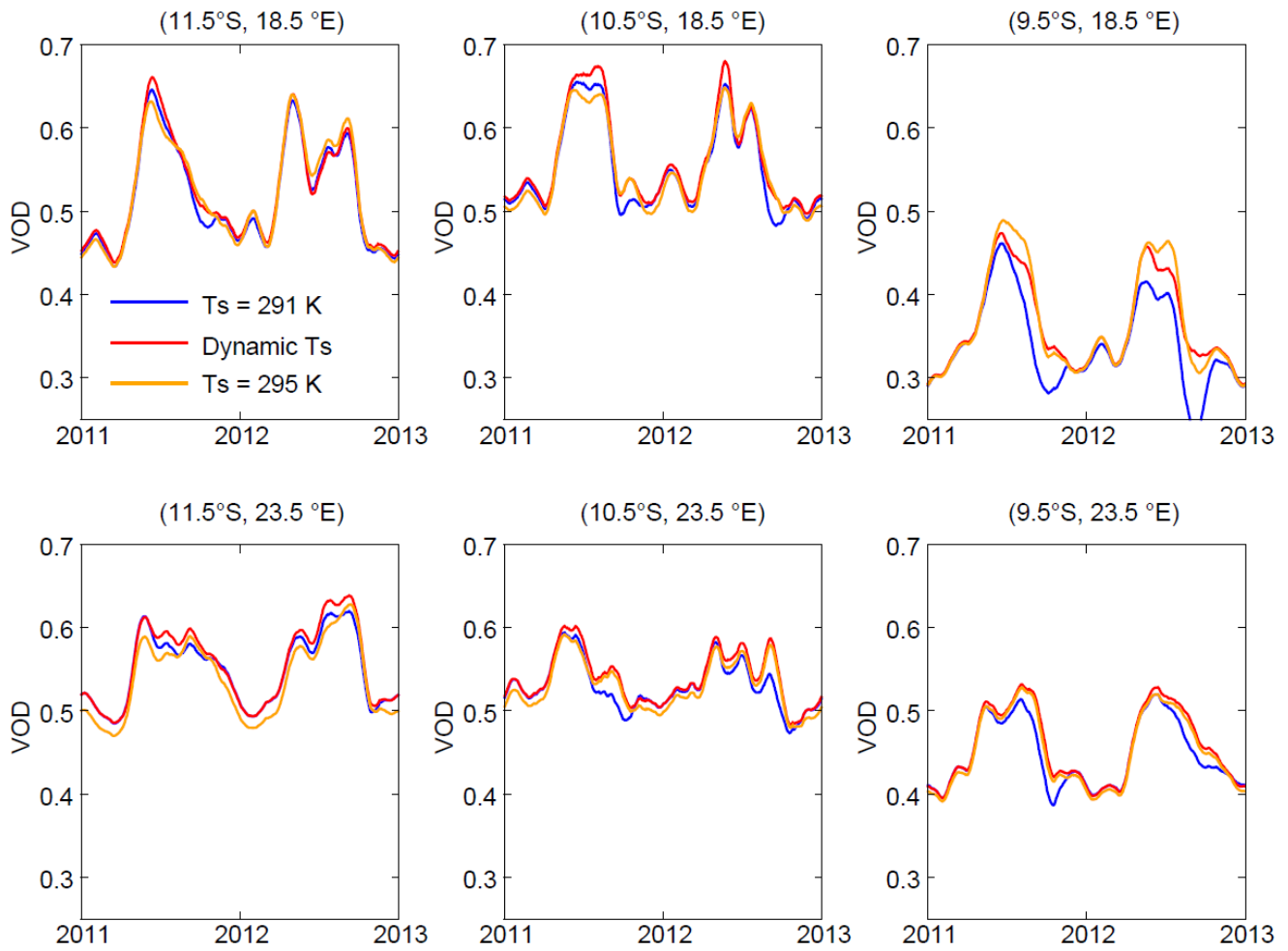
560

561 **Extended Data Figure 8:** Seasonal changes of L-VOD with soil surface roughness (HR) set to 0.2, 0.3 (used value in SMOS-
 562 IC) and 0.4, respectively over six evenly distributed sites (one pixel for each) in the Miombo region (the upper left site is from
 563 the same location as in Figure 5b). Note that curves with different HR settings almost totally overlap each other.



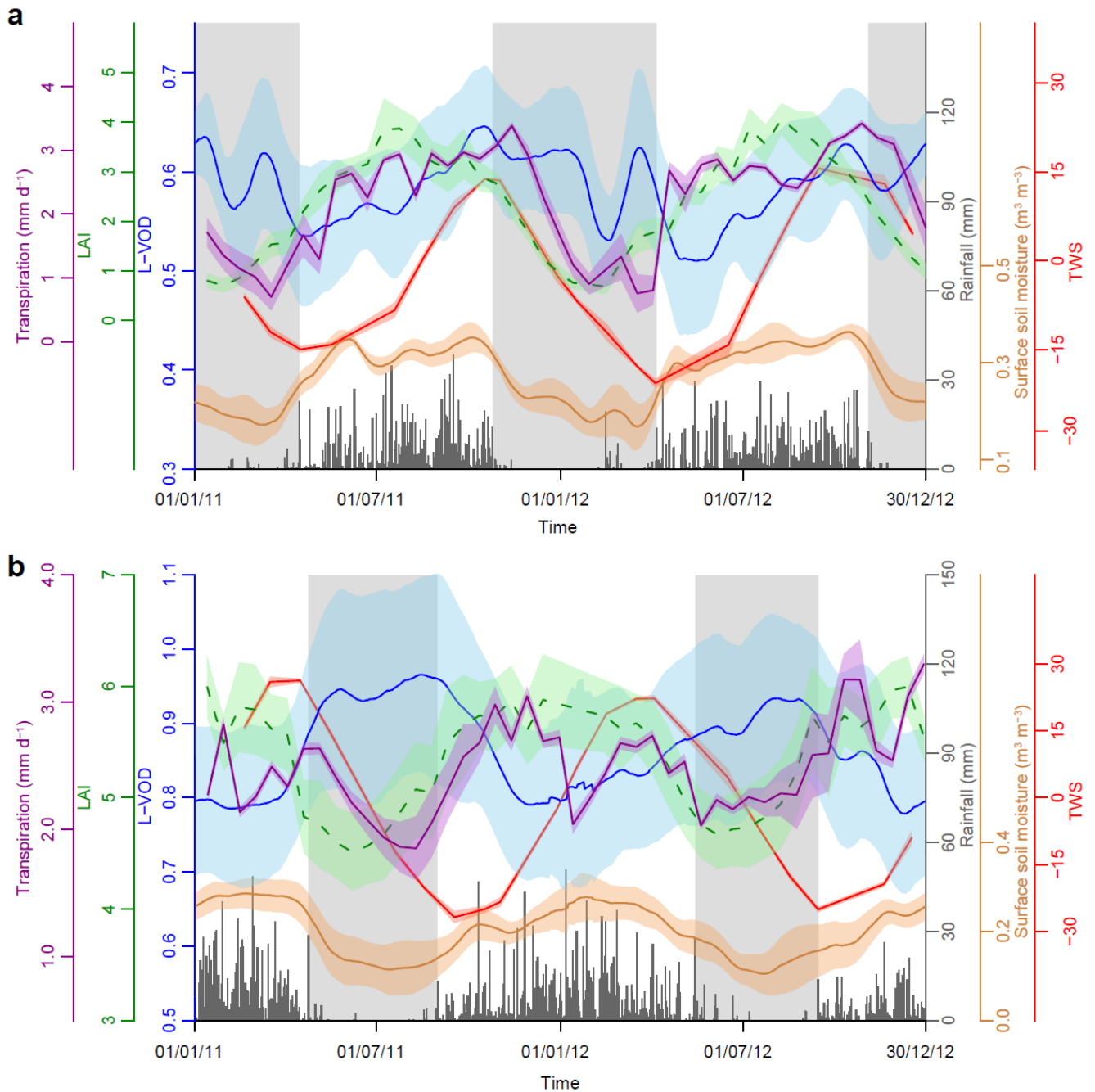
564

565 **Extended Data Figure 9:** Seasonal changes of L-VOD with effective scattering albedo (Omega) set to 0.05, 0.06 (used value
 566 in SMOS-IC) and 0.07, respectively over six evenly distributed sites (one pixel for each) in the Miombo region (the upper left
 567 site is from the same location as in Figure 5b).



568

569 **Extended Data Figure 10:** Seasonal changes of L-VOD with effective temperature (T_s) set to constant values of 291 K and
570 295 K over the season, and to the dynamic ECMWF estimations (used in SMOS-IC), respectively over six evenly distributed
571 sites (one pixel for each) in the Miombo region (the upper left site is from the same location as in Figure 5b).



572

573 **Extended Data Figure 11: a**, An example time series (2011-2012) of plant water storage (L-VOD), terrestrial groundwater
 574 storage anomaly (TWS), surface soil moisture, rainfall, transpiration, and canopy phenology (LAI) for northern African
 575 woodlands located in south of Central African Republic centred at 5.5°N, 16.5°E. The coloured shaded curves represent the
 576 standard deviations ($n = 16$ for all except TWS where $n = 3$). The grey shaded rectangles indicate the dry seasons. Tree cover
 577 = 67%. **b**, Same as for **a**, but for a location in the Brazilian Cerrado region centred at 11.5°S, 59.5°W. Tree cover = 71%.