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Interactive comment on "Patterns of plant rehydration and growth following pulses of soil moisture availability" *by* Andrew F. Feldman et al.

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Reviewer 2: Feldman et al. use SMAP soil moisture and VOD data to show that plant response times to moisture pulses (characterized by "time-to-peak" between the start of the soil moisture drydown and peak VOD") are differentiated between humid regions (with tp of around zero) and dryland regions (tp >=1 days and up to >3). Furthermore, the authors use a satellite LAI dataset to distinguish between plant rehydration versus plant growth mechanisms for explaining the dryland VOD increase. From this latter analysis, they demonstrate that at shorter timescales (tp 1-3) the VOD increase is dominated by plant rehydration, and at longer timescales (tp >3) the VOD increase is more dominated by plant growth that occurs when antecedent conditions are wetter and the pulses of a higher magnitude.

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This study represents an important advance in our ability to remotely sense relatively short timescale vegetation responses to rainfall pulses, and further adds broader scale evidence to support the pulse-driven growth in dryland regions. The study context, questions, methods and results are clearly described and analyzed. The authors neatly address many caveats of the work, including limits and uncertainties associated to temporal sampling interval of the satellite instrument. I think this is exciting work that offers promise for exploring plant responses to moisture pulses in more depth when satellite sensor temporal sampling interval and spatial resolution are increased.

Authors: Thank you for your constructive comments. Please see our replies to your comments below.

Reviewer 2: Main comments My only remaining questions are relatively minor and are related to the LAI data. I appreciate the need to use a geostationary product given you require a high tem- poral resolution - thus, the choice of the EUMETSAT LSA SAF LAI product. Satel- lite LAI data are known to agree well in terms of temporal dynamics but differ in terms of absolute magnitude (e.g. Garrigues et al., 2008; Fang et al., 2013). I am wondering how biases in magnitude would impact your results, if at all? Perhaps the rates of change in LAI would be consistent across products.

Authors: The analysis makes use only of the temporal dynamics rather than the absolute magnitude. Figure 4 is evaluating the rates of change (time derivative). Therefore, subtracting out the mean value would produce the same results and similarly using the related fraction of vegetation cover product produces the same qualitative results as that in Figure 4. Furthermore, we are less concerned about the magnitude of LAI changes and more concerned about whether LAI is increasing or decreasing and how the sign of change influences the time to peak (tp). We will add a new figure (proposed figure 4) as shown below in Fig. R1 to make this point clearer and to more clearly introduce original Fig. 4.

Reviewer 2: Did the authors look at any other optical geostationary satellite data products that are related to leaf growth/vegetation activity (NDVI, FAPAR, LAI)? I know there are not as many geostationary optical satellite products related to vegetation activity, and I confess I am not as familiar with these products, but I think there are some. For example, the GeoNEX products (Wang et al., 2020) and related to this I think is the NDVI from the AHI sensor (Miura et al., 2019). NDVI can be calculated from GOES-16/17 (https://www.ospo.noaa.gov/Products/land/ vegetation.html).

Authors: To the authors knowledge, there are no other geostationary satellites that would provide a one-to-one comparison with the MSG-SEVIRI satellite we are using in Africa. The MSG series is included in the GeoNEX products mentioned here.

The AHI Sensor covers primarily Japan and other Pacific Islands which will not provide a one-to-one comparison with Fig. 4 and also occurs in a region where the microwave data are less available due to radio frequency interference (quality flags due to interference from telecommunication).

The GOES-16/17 provides observations over primarily the North American region which does not provide a one-to-one comparison with results found in Africa and a comparison between Africa and North America behavior would not provide clear implications about LAI uncertainty. It may instead provide insights into the less-spatially extensive Southwest US dryland regions relative to African drylands and potential differences in responses of the biomes therein.

Note that we repeated Fig. 4 using SEVIRI FAPAR which provides similar qualitative results. See Fig. R2 below. While FAPAR is retrieved from the same satellite, it uses different frequencies of measurements and a different algorithmic approach than for LAI such that is provides at least a partially independent vegetation index from that of LAI.

Reviewer 2: A different point related to the LAI data: How noisy are the daily fluctuations? Are the changes in LAI you see after moisture pulses clearly detectable from the noise? Are the changes you see in LAI within the product uncertainty?

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Authors: In the SEVIRI LAI data, a filter is applied to mitigate cloud cover contamination: previous days before the measurement are nonlinearly averaged where the most recent days contribute more to the displayed value. Daily fluctuations are therefore inherently smoothed. The post-processing smoothing technique thus obscures this error/uncertainty estimation. The available uncertainty metrics provided from LandSAF are related to the magnitude of the LAI measurements and bias compared to ground measurements rather than a more desirable error standard deviation estimate for this application here, which would quantify how much of a daily LAI change is due to noise. We are not aware of such standard deviation LAI estimates and could not find any available in the literature.

Ultimately, we are most concerned with whether SEVIRI is confidently estimating the LAI seasonal cycle. Even if there is an uncertain dLAI/dt value on a given day, we are more interested qualitatively if this value is positive, negative, or near zero during a given soil moisture drydown. Therefore, as long as the seasonal cycle of LAI is well resolved with these daily measurements, we can be confident that a dLAI is capturing a growth or senescence stage. The proposed new Fig. 4 reflects this idea (see Fig. R1 above). We are confident in our dLAI/dt estimates about the season changes in LAI for several reasons:

1) SEVIRI LAI samples effectively every 3-5-days compared to low Earth orbit satellites like MODIS which effectively sample every 15-20 days (Fensholt et al. 2006). This is due to cloud cover contamination which obscures the SEVIRI 15 minutes actual sampling and the MODIS 1-2 day actual sampling. Based on this consideration, SEVIRI is better able to resolve the seasonal cycle, especially during the wet season (of most interest for detecting the tp>3) compared to noisier measurements from low Earth orbit (MODIS) (Gessner et al. 2013). See Fig. R3 below. 2) We are estimating average dLAI/dt over $\sim$10 day stages (during soil moisture drydowns), which become insensitive to whether or not a given day change of LAI is detectable above a noise level. We are thus confident in determining whether a 10 day trend in LAI is positive or negative,

especially given that SEVIRI LAI is able to resolve the seasonal cycle. 3) Uncertainties are lowest in Africa due to its lower view angle and especially in regions with more herbaceous vegetation (Garcia-Herrero et al. 2013). Therefore, the regions we are evaluating (see Fig. 4) generally have the lowest errors compared to other regions measured by SEVIRI.

In the reply to the next comment, we propose changes to specific sections.

Fensholt, R., Sandholt, I., Stisen, S., Tucker, C., 2006. Analysing NDVI for the African continent using the geostationary meteosat second generation SEVIRI sensor. Remote Sens. Environ. 101, 212–229. https://doi.org/10.1016/j.rse.2005.11.013 García-Haro, F.J., Camacho, F., Meliá, J., 2013. The EUMETSAT Satellite Application Facility on Land Surface Analysis Product User Manual Vegetation Parameters (VEGA) 401, 1–46. Gessner, U., Niklaus, M., Kuenzer, C., Dech, S., 2013. Intercomparison of leaf area index products for a gradient of sub-humid to arid environments in west africa. Remote Sens. 5, 1235–1257. https://doi.org/10.3390/rs5031235

Reviewer 2: As the authors nicely discuss, these results are in line with many field-based studies. Therefore, I do not expect different LAI data, or any other optical satellite data related to leaf growth, to have a strong impact on the key findings here. I would just be curious as to how much of a difference the LAI (or NDVI etc) dataset makes and would be interested to see a brief discussion on any caveats related to LAI data noise and algorithm uncertainty.

Authors: As stated in our replies to the previous comments, there is not another feasible LAI dataset to directly compare with the SEVIRI LAI data in this study in Africa. Another geostationary product could be used in another region and it would be unclear whether differences would be due to vegetation/climate or LAI dataset differences. Low Earth orbit satellites like MODIS are not feasible for this application since they are unable to resolve the seasonal cycle, especially during the wet season (see our reply to the previous comment).

We will revise and extend the methods paragraph in lines 120-130 to add a more comprehensive discussion of the LAI data and its uncertainties that makes the following points: That we are confident in LAI detecting increases over 1-2 weeks because: (1) SEVIRI LAI resolves the seasonal cycle of growth and senescence stages well due to rapid sampling and filtering techniques which can resolve the seasonal cycle even during the wet season. See an example in Fig. R3. (2) Because of (1), we are confident we can detect the stage of the LAI seasonal trend over a 1-2-week period which less insensitive to uncertainties in daily LAI rates of change (3) LAI retrievals in herbaceous biomes of Africa, evaluated here, have the lowest uncertainty (4) Use of LAI data is primarily for qualitative purposes (increase/decrease) which makes our analysis less sensitive to noise considerations at daily scales and to biases in absolute LAI magnitudes.

We will add a statement such as: "Ultimately, we are more interested in qualitatively increasing trends in LAI rather than the magnitudes of LAI rates of change which are less certain." in line 253 to denote that we are primarily focused on qualitative increases rather than LAI magnitudes. We will also add a statement about why we are confident in the trends in the discussion in Line 350 that reflect the points above as well. Finally, we will add a new figure as new Figure 4 (Fig. R1), that shows how we are using the LAI data primarily as a binary metric as to whether tp is estimated during a growth period.

Reviewer 2: I initially had a question has to why the LAI be decreasing across shorter tp timescales, and does that mean the positive changes in VOD actually reflect an even higher in- crease in plants' relative water content? This seems to be happening mostly in the Sahel. I then read in the discussion that this is because these events are mostly detected during periods when shrubs are shedding leaves, which makes sense given the shorter VOD increases are happening in drier periods. Have I understood correctly, or could there be any other reason?

Authors: Your interpretation is consistent with ours that a decrease in LAI/biomass

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would suggest that the positive increase in relative water content reflected in VOD is likely being subdued by the biomass decrease. We will extend our statement in line 375 to read: “They can occur even when biomass is decreasing (Fig. 4; such as leaf off), where the relative water content increases are likely larger than what the raw VOD increasing signal suggests.”

Reviewer 2: For longer duration tp > 3 the Sahel also has some decreases in LAI, with weaker increases than other regions in Africa. Is there any other reason to think the LAI in the Sahel is either less reliable or more influenced by other factors that are confounding these results?

Authors: Based on various in-situ assessments and validation reports, there is no evidence provided that the LAI uncertainty in the Sahel would be less certain than LAI measurements in similar climates of Southern Africa. Furthermore, soil contamination mitigation techniques (with a Gaussian mixture model) are implemented within the LAI algorithm to reduce sources of error from bare soil common in less vegetated regions such as the Sahel.

We assessed the pixels in the Sahel where LAI decreases during tp>3 on average. These appear to be related to LAI seasonal cycles where, in this specific region, dLAI/dt differentially has a greater magnitude slope (absolute value) during the senescence stage than the dLAI/dt during the growth stage. There are large negative dLAI/dt during tp>3 detected periods during the senescence stage that then bias the overall mean dLAI/dt estimate. This does not occur in nearby pixels in the Sahel or in similar climates of Southern Africa where LAI increases during tp>3 on average. See Fig. R4 below for an example of this scenario where the blue line shows how the dLAI/dt decreases are differentially larger in magnitude than the increases in these regions in question in the Sahel. This does not occur in other regions (such as for the red and green lines). We ultimately could not determine a method to objectively remove cases of these LAI decreases.

Ultimately, we are attempting to quantify the overall trends in growth and avoid interpreting specific pixels, acknowledging that there that there will be cases of noisy tp estimates with the VOD time series. For example, there are may be cases where a VOD increase was truly tp = 2 days but a single noisy observation created a tp = 5 day estimate. In taking the average over the pixel, we intend to detect the mean responses amongst uncertain estimates. See our section 3.4 and specifically lines 318-319. Therefore, we anticipate biases in even full pixel estimates of tp which may result in tp>3 falsely related to decreases in LAI. Based on these considerations, we avoid interpreting results in specific pixels. We will make this point clearer in line 231.

Reviewer 2: Line 433-435: I am not sure this analysis fully supports this conclusion: "demonstrating evidence for the pulse-reserve hypothesis and suggesting sub-weekly (rain pulse) rather than seasonal phenological controls on growth (Noy-Meir, 1973)". As the authors have demonstrated, plant growth with longer tp periods are associated with wetter preceding conditions and stronger pulses. This could be in seasons that are already favorable for growth (as the authors state in lines 368-369), suggesting seasonal phenological controls (which may include temperature constraints) are still important. The pulses just result in that extra bit of growth.

Authors: This is an excellent point. As the reviewer points out, we do acknowledge that there is a phenological component to the growth in lines 368-369. Therefore, the statement about phenological controls in line 433 is a misstatement of the results. We propose to change the sentence in line 433 in the conclusions to be more consistent with our discussion statements that are similar to the point made by the reviewer: "Therefore, dryland vegetation intermittently upregulates and grows after individual rainfall events, demonstrating spatially-extensive evidence for the pulse-reserve hypothesis. Specifically, we show that there is a component of growth linked directly to individual rainfall events in addition to any continuous seasonal growth (Noy-Meir, 1973)."

Reviewer 2: Given the studies that show inter-annual variability in net CO2 uptake is strongly linked to days with peak gross CO2 uptake (Zscheischler et al., 2016), I am wondering whether increases in leaf growth during the longer tp periods translate to increases in carbon uptake. Perhaps SIF data would be useful in this regard. However, this is probably beyond the scope of this study.

Authors: While evaluating carbon fluxes/photosynthesis is beyond the scope of this study, we have another study under review and likely to be published in time to reference in this paper. In that paper, we show that carbon fluxes at flux towers show similar signatures to VOD responses here, specifically that the greatest and longer duration increases in NEP occur after larger rainfall events on wetter surfaces.

Reviewer 2: Minor comments Fig. 4C is not referenced in the text.

Authors: Good catch. We will mention 4C in the parentheses in addition to 4A and 4D in line 228. We will also denote 4C in the parentheses in line 375.

Reviewer 2: Fig. S5: describe sub-figure C in caption.

Authors: Good catch. In Fig. S5 caption, we will add: "(C) Incorporating random noise into the algorithm appears to increase false detection of non-zero tp the most. Ultimately, all effects together still result in frequent correct detection of true tp of zero."

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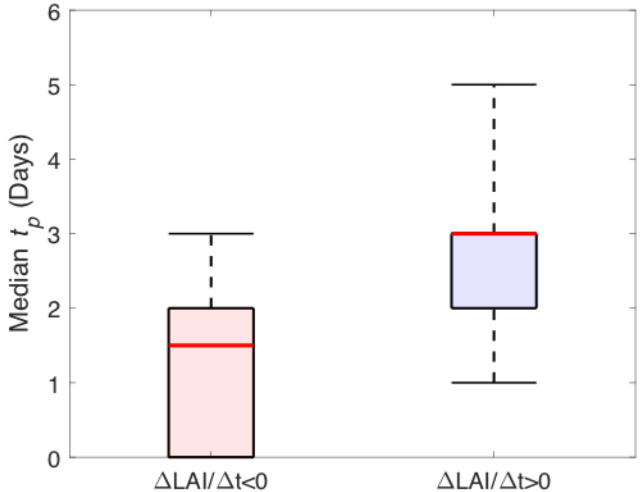

Fig. 1. Fig. R1. Proposed new Fig. 4 in the manuscript. Growth increases the timescale of plant water content in African regions with median tp ≥1 day. Medians of the two bins are significantly different (p<0

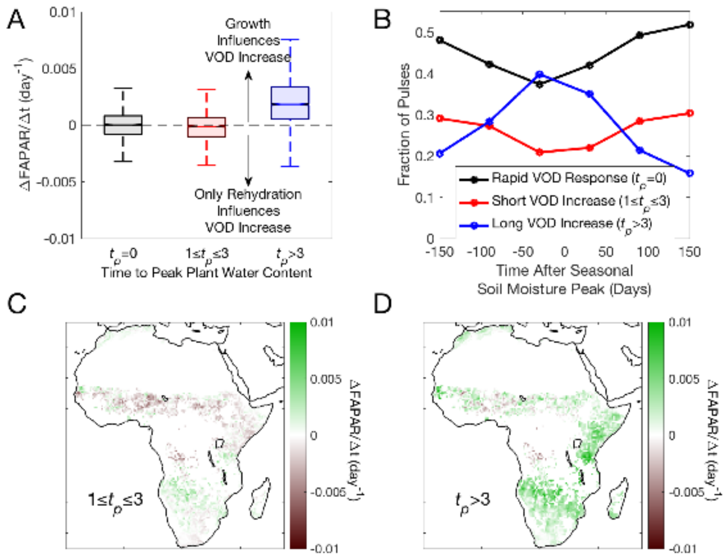

Fig. 2. Fig. R2. Figure 4 repeated with FAPAR which is derived from a separate algorithmic approach in LandSAF.

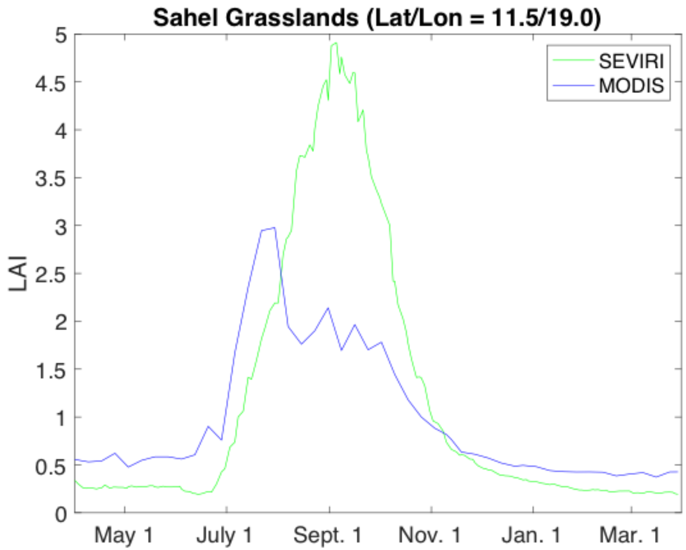

Fig. 3. Fig. R3. Example Sahel Grasslands pixel with seasonal cycle of SEVIRI and MODIS LAI. MODIS is less able to resolve the seasonal cycle during the wet season due to less frequent sampling than SEVIRI.

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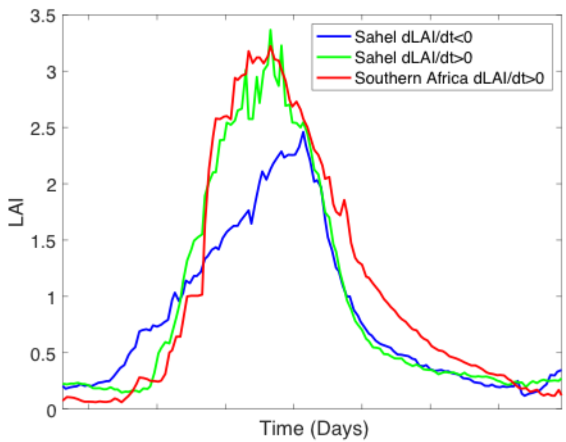

Fig. 4. Fig. R4. LAI annual time series at example pixels where dLAI/dt was positive and negative.