Dear Dr Forkel,
We wish to thank you for your thorough proofreading and your relevant comments. They were taken into account in order to improve the manuscript.
In that respect, the contributions of VWC and AGB in VOD were further discussed. The exclusion of Australia and of regions subject to seasonal fires was also better justified. The suggested references have been included. Other minor changes were made according to your suggestions, in order to improve the clarity of the text and of the figures.
Please find below in blue font a detailed description of how we addressed your comments.
Sincerely,
Emma Bousquet et al.

RC2

<u>Review of the manuscript "SMOS L-VOD shows that post-fire recovery of dense forests is slower than what is depicted with X- and C-VOD and optical indices" by Bousquet et al. 2021</u>

The study investigates the temporal anomalies of different remotely-sensed climate variables and vegetation properties before and after fire. The main finding is that L-VOD recovery slower after fire than X-VOD, C-VOD or optical vegetation indices. The study provides an important contribution to the research on the understanding of VOD data in different wavelengths and on the use of VOD to study fire. The text is written in an easy to understand language, however some sentences are written too simple and are unspecific and by this make partly wrong statements (see specific comments).

Fire is both driven by fuel loads and fuel moisture (Chuvieco et al., 2014) and VOD is sensitive both to biomass and fuel moisture content (FMC), or vegetation water content (VWC) (Konings et al., 2019). Especially, X-VOD is more sensitive to FMC than other microwave-derived surface properties (Fan et al., 2018). Hence VOD was already successfully used in data-driven fire models (Forkel et al., 2017; Kuhn-Régnier et al., 2021). However, it is not yet clear how the different VOD bands are sensitive to either biomass or FMC and hence of the biomass- or moisture-"component" of VOD is more important for fire prediction. The same question is true for post-fire recovery: Does VOD measure really a recovery of biomass or a recovery of the fuel moisture? Note that different changes in VOD and optical indices and their relation with land cover trends have been also investigated in Andela et al. (2013). Those sensitivities of VOD to biomass and moisture are important to consider in the context of this study, however, those lines of thought were not included in the introduction and/or discussion. Hence, the objective of the study is also not entirely clear. Are you aiming to use VOD as a proxy for post-fire biomass recovery? If yes, how could you disentangle the moisture effect? The role of biomass and moisture on VOD should be introduced in chapter 1 and discussed in the discussion.

This paper aims at studying post-fire vegetation recovery through four variables, EVI, X-VOD, C-VOD, and L-VOD. We cannot study biomass recovery alone because EVI represents only the greenness of vegetation, and VOD is indeed sensitive to both biomass (AGB) and vegetation water content (VWC). This was stated at line 144 and briefly discussed at lines 388 for Australia and at lines 463 for the dense broadleaf ecosystem. Disentangling the contributions of AGB and VWC in the VOD is very tricky and has not been done yet, because they are strongly linked (Konings et al., 2019). We can only provide assumptions. For example, when VOD and SM evolutions follow each other, we can assume that the fuel moisture (VWC) is impacted. Monitoring directly AGB is complex since monthly AGB maps do not exist. In the first part, we considered the forest loss from Hansen et al. (2013) "lossyear" product to corroborate that fires lead to biomass destruction, and not only to vegetation drying. We agree to develop the discussion on that matter though, thanks to the relevant references you provided us. For that, we added (modifications appear in red):
L. 72 : "*Indirectly, drought also causes leaf shedding, branch losses, and a decrease in fuel moisture content, which increases forest flammability (Nepstad et al., 2001; Pausas and Bradstock, 2007; Chuvieco et al., 2014). Surveying the soil moisture (SM) and the vegetation water content (VWC) could then be a good indicator for fire risk detection. [...] AMSR-E VOD was successfully used in data-driven fire models (Forkel et al., 2017; Kuhn-Régnier et al., 2021).*"
L. 99 : "*Microwave VODs are also sensitive to VWC and can help to monitor the biomass status (Fan et al., 2018; Konings et al., 2019).*"

L. 146 : "*No clear approach exists for disentangling the contributions of AGB and VWC in the VOD because of the co-sensitivity of microwave observables to both quantities (Konings et al., 2019).*"
L. 381 : "*In South-East Australia, a strong pre-fire drought is visible in the climate variables but also in the mild decrease of vegetation variables (Fig. 3a), linked with VWC deficit.*"
L. 413 : "*A substantial increase in VVs occurs 1–2 years before fire, which implies an increase in vegetation density, e.g. available fuel. Immediately before fire, both VOD and SM values drop down, suggesting a decrease in VWC, especially over grasslands (Fig. 5a). The increase of vegetation material combined with the decrease of VWC may contribute to trigger large wildfires (Forkel et al., 2017; Kuhn-Régnier et al., 2021).*"
L. 456 : "*Indeed, rainfall shortage generates high water deficits (i.e. high negative TWS and SM anomalies), which cause tree mortality, leaf shedding (visible in pre-fire EVI decrease) and thus increase fuel availability (Aragão et al., 2018). Nevertheless, no pre-fire VOD decrease is observed here, showing that tree species of dense forests can maintain their VWC.*"
L. 478 : "*Thanks to its sensitivity to coarse woody elements and to its deep penetration through the vegetation layer, L-VOD is better correlated to high AGB than other VVs (Rodriguez-Fernandez et al., 2018), and could be used for post-fire recovery monitoring over dense forests. One must keep in mind that not only the biomass volume (AGB) but also the biomass status (VWC) is depicted in VOD.*"

Like the second referee, I am puzzled about the selection of fires for the analysis (Fig. 4a). Globally, fire activity is strongest in the African Savannahs (mostly in the Sahel), in northern Australia and South America (Giglio et al., 2013; Andela et al., 2019). However, the Sahel and Australia (and the Mediterranean) are almost completely missing in the selection of fires. What are the reasons? Does it make sense to not consider some of the most fire-prone regions in the analysis? You need to revise this (or clarify it).

The Sahel and the Mediterranean are missing because of the selection method chosen : "*Fires with a number larger than 5 in the MODIS dataset were considered, and only if no other fire occurred on the same area (number lower than 2 apart from the main fire event). This was done to observe only the impact of the major fires, without any other disturbance*" (lines 280-282). In the Sahel, these conditions are not fulfilled because seasonal fires occur and the second threshold is exceeded (Fig. R1).
The above paragraph was unclear and was replaced by : "*To properly observe the factors and impacts of a fire event without any other disturbance, only 25 km regions showing a unique and heavy fire over the time period were considered. This excluded areas with regular seasonal fires, such as the Sahel region. For that, a minimum threshold of 5 was applied on the maximum number of fires ; and a maximum threshold of 2 was applied outside the main fire event period (i.e. outside the period -6/+6 months around the fire event).*"
We also added the land cover "shrublands" (IGBP labels 6 and 7) to the biome "tropical and subtropical savannas" (IGBP labels 8 and 9); and "croplands" (IGBP label 12) and "natural vegetation mosaic" (IGBP label 14) to the biome "grasslands" (IGBP label 10). Figure 4 of the manuscript was replaced by Fig. R2 below.

As for Australia, by using the methodology described in Sect. 3.2, the majority of fires in Australia occurred in 2012 in the Outback (shrublands) and in 2019/2020 in the South-East (broadleaf forests). These two cases correspond respectively to the very beginning and the end of the study period. This prevents a robust pre- and post-fire study, especially since these fires become predominant in the global dataset (Fig. R3): Australia represents 57% of the total fires for the savannas and shrublands biome, and 54% for the dense broadleaf forests biome. This continent is strongly over-represented in the MODIS active fire product due to the large size of the fire events over this continent (Giglio et al., 2016). Thus, we reckon that it is more consistent not to analyse those events in the current study. We will certainly revisit the study in Australia with more hindsight in the future, once the time series after the fire will be long enough to properly analyse the vegetation recovery. The text was modified as follows to better justify this exclusion: "*Australia was excluded because numerous fires were detected in 2012 in the Outback (shrublands) and in 2019/2020 in the South-East (broadleaf forests), which prevailed over the global dataset (~55% of the points) and prevented to perform a robust pre- and post-fire study.*"
In order not to omit this continent from the study, we included a detailed case study in South-East Australia in the first part (Fig. 3a).

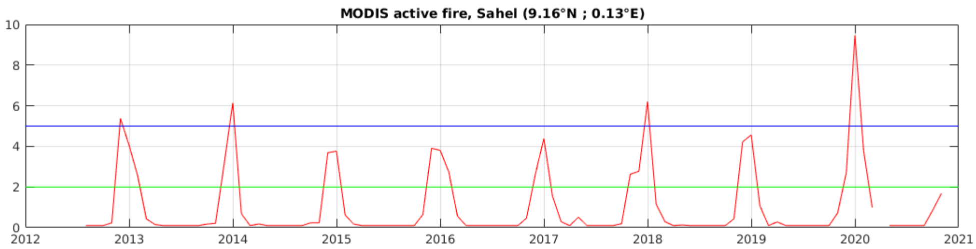

Figure R1 - Time series of the number of fires (MODIS active fire product) over a 25 km pixel in the Sahel (red). The blue line represents the minimum threshold s1 = 5 for the strongest fire event detection; and the green line represents the maximum threshold s2 = 2 for the rest of the period (which is exceeded).

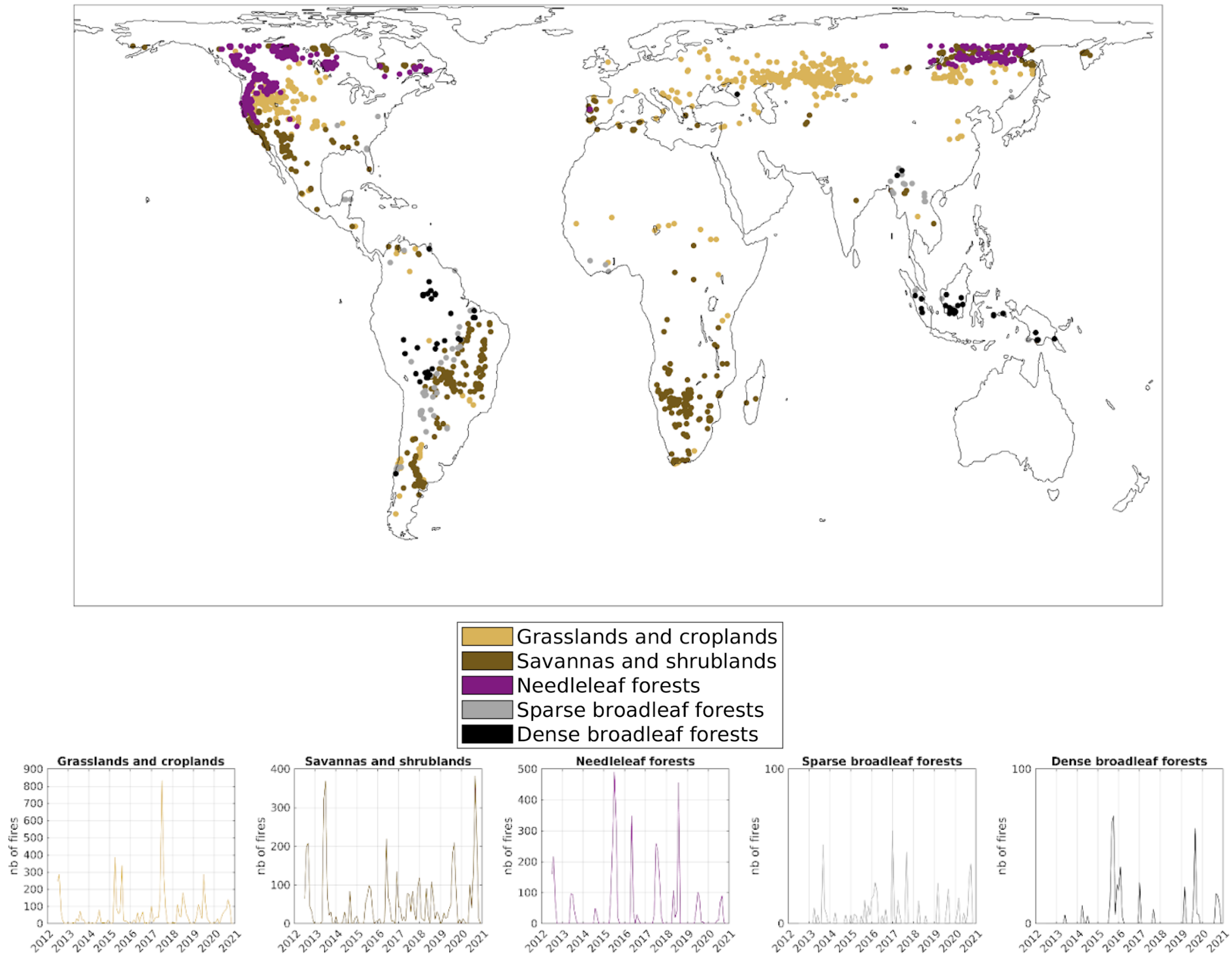

Figure R2 - Location of the selected fires and histograms of the fire dates, for grasslands and croplands (IGBP labels 10, 12, and 14), savannas and shrublands (IGBP labels 6, 7, 8, and 9), needleleaf forests (IGBP labels 1 and 3), sparse broadleaf forests (IGBP labels 2 and 4, AGB ≤ 150 Mg ha^{-1}), and dense broadleaf forests (IGBP labels 2 and 4, AGB > 150 Mg ha^{-1}). Australia was excluded as well as areas affected by water, snow, or strong topography (see Sect. 3.1).

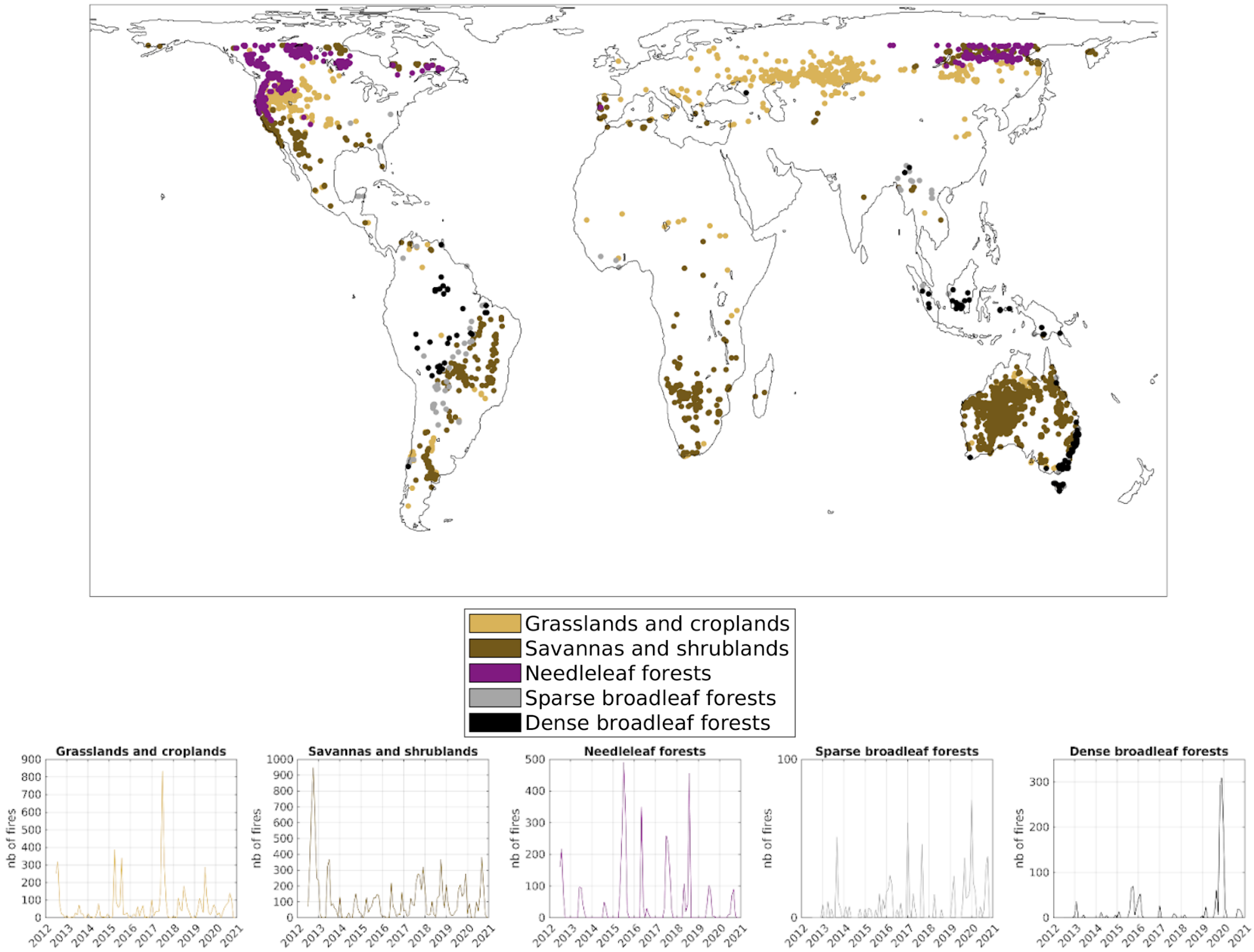

Figure R3 - Same as Fig. R2, without the exclusion of Australia.

<u>Specific comments</u>

L 34: “Authors found“ – unclear which authors are meant

It refers to the previous authors (Silva et al., 2018). The sentence was modified as follows: “*Specifically, they found [...]*”.

L 94-95: The sentence is not clear and wrong. L-band was already used in conjunction with other VOD data. See for example (Fan et al., 2018)

The reviewer is right. We modified this sentence by: “*This study also presents for the first time L-band used in conjunction with other sensors, from optical-infrared (EVI) to microwave X- and C-bands, for the study of post-fire vegetation recovery.*”

L 96: Using the abbreviation “VV” for vegetation variables in a study that makes use of microwave remote sensing data is not ideal because VV stands for vertically polarized sensed and received radiation. In order to avoid confusion, I recommend using another abbreviation.

We do not think there is much room for confusion as radar is not used in this study. However, following the reviewer comment, we decided to remove the abbreviation “VV”.

L 208-209: What is the size of those fires relative to the spatial resolution of the SMOS data? How many pixels are included in those fires? Did you apply any threshold for minimum fire sizes in order to select the case studies?

MODIS Active Fire product is a quantification of the number of fires observed within a 1000 km² area. A fire must cover at least ~ 1000 m² to be detected (see Sect. 2.1). The thresholds applied to the MODIS number of fires for the selection of the studied regions are described at lines 280-282. We added “*(see Sect. 3.2)*” to

facilitate the understanding. For the three case studies, the selection was arbitrary and not based on the MODIS number of fires. We added the description of the number of fires observed in Fig. 3 in Sect. 4.1:
"In evergreen forests of the South Coast of New South Wales in Australia (Fig. 3a), fires reach a maximum in January 2020 (mean number of fires = 8)."
"The Mendocino Complex was the strongest of the three case studies, with 20 fires observed in average in August 2018."
"In the dense rainforest near Santarem (Brazilian Amazon), only 4 fires were detected in December 2015 (Fig. 3c), but this value may be underestimated due to cloud coverage (Giglio et al., 2020)."

L 256: Here a caption for a sub-chapter is missing because the chapter is still about the Santarem case study and not about the data analysis.
The reviewer is right, we added a subsection *"3.1.4 Time series anomalies computation"*.

L 274: I don't understand the point iii – You excluded entire Australia from the global analysis? Why? Can you improve this description.
We agree that the justification of the exclusion of Australia was not clear enough. We modified this paragraph accordingly (see the answer to your second major comment).

L 280-285: How was the anomaly computation done if a pixel experienced multiple fires?
Pixels experiencing multiple fires were removed because we wanted to observe the factors and impacts of a fire event without any other disturbance (see the answer to your second major comment).

L 413: Those time lags between fire and fuel availability were also recently reported here (Kuhn-Régnier et al., 2021).
Thank you for this reference. It was added in the text (see the answer to your first major comment).

L 419: What does L-VOD "measure" in grasslands and savannahs? L-VOD should be close to zero in grasslands as the L-band microwave penetrate the grass layer. Can you provide some more explanation and references about the sensitivity of L-VOD in grasslands?
Over grasslands, L-VOD is indeed very small but not negligible. Actually, the VOD is never zero when there is vegetation. SMOS L-VOD = 0.22 on average over grasslands, which is quite low (L-VOD spans from 0 in deserts to ~1.3 in dense forests). The effects of grasslands, fallow and crops have been reported in many studies (Wigneron et al., 2004; Wigneron et al., 2012; Togliatti et al., 2019; Togliatti et al., 2021). L-band penetrates through the grass layer but is still attenuated by it, in particular when its water content is significant (Saleh et al., 2006). Moreover, some grasslands are made of a thick grass layer which can reach one metre or more, and thus are not transparent for L-band. Panciera et al. (2011) characterised grasslands and croplands as "moderate" canopy conditions.
In savannas and woody savannas, SMOS L-VOD = 0.33 and 0.49 respectively. Savannas are described as "lands with herbaceous and other understory systems, and with forest canopy cover between 10−30%" (Broxton et al., 2014). The sparse trees of this mixed ecosystem contribute predominantly to the L-VOD signal.

L 425-426: Note that there are much more differences in fire regimes between North American and Siberian boreal forests (Rogers et al., 2015). In your analysis, different signals might be mixed and hence it would be better to investigate the two regions separately.
Thank you for this useful reference. It was added in the manuscript. Rogers et al. (2015) explained that fires in North America are predominantly high intensity crown fires, whereas fires in Eurasia are generally lower intensity surface fires, which are less destructive for the vegetation. This was already written in the discussion (lines 436-438): "in North America, boreal forest fires are predominantly stand-replacing and high-intensity crown fires (Stocks et al., 2004; Jin et al., 2012). In Eurasia, most fires occur as surface fire and are usually of low to moderate intensity (de Groot et al., 2013)."
Rogers et al. (2015) also stated that these different fire regimes are due to different tree species.
We plotted separately the time series on the two regions (Fig. R4). We can observe some similarities: i) a pre-fire surplus in vegetation variables; ii) high temperature and low hydrologic variables during fire; iii) a

strong impact of fire on VVs, mainly EVI; iv) a long recovery phase. Some discrepancies are also visible: in North America, i) pre-fire SM and TWS deficits are higher, while T surplus is lower; ii) EVI and L-VOD are more impacted by fire, while C- and X-VOD are less impacted; iii) L-VOD and TWS continue to decrease two years after fire; iv) EVI and L-VOD recover slower than in Eurasia (~ 3 years vs ~ 2 years for EVI, ~ 4 years vs ~ 2 years for L-VOD). The latter observation can be due to the fact that, as the reviewer states, North American crown fires are more destructive for the vegetation than Siberian surface fires.
These time series (Fig. R4) will be provided in Supplementary Material, and the associated observations added in the discussion: "*Fires in North America are predominantly stand-replacing and high-intensity crown fires (Stocks et al., 2004; Jin et al., 2012), whereas fires in Eurasia are generally lower intensity surface fires, less destructive for the vegetation (de Groot et al., 2013). These different fire regimes are influenced by tree species (Rogers et al., 2015). Time series were plotted separately over each continent (Fig. S1). L-VOD and EVI recover slower in North-America than in Eurasia (~ 4 years vs ~ 2 years for L-VOD, ~ 3 years vs ~ 2 years for EVI), confirming these different boreal fire regimes.*"

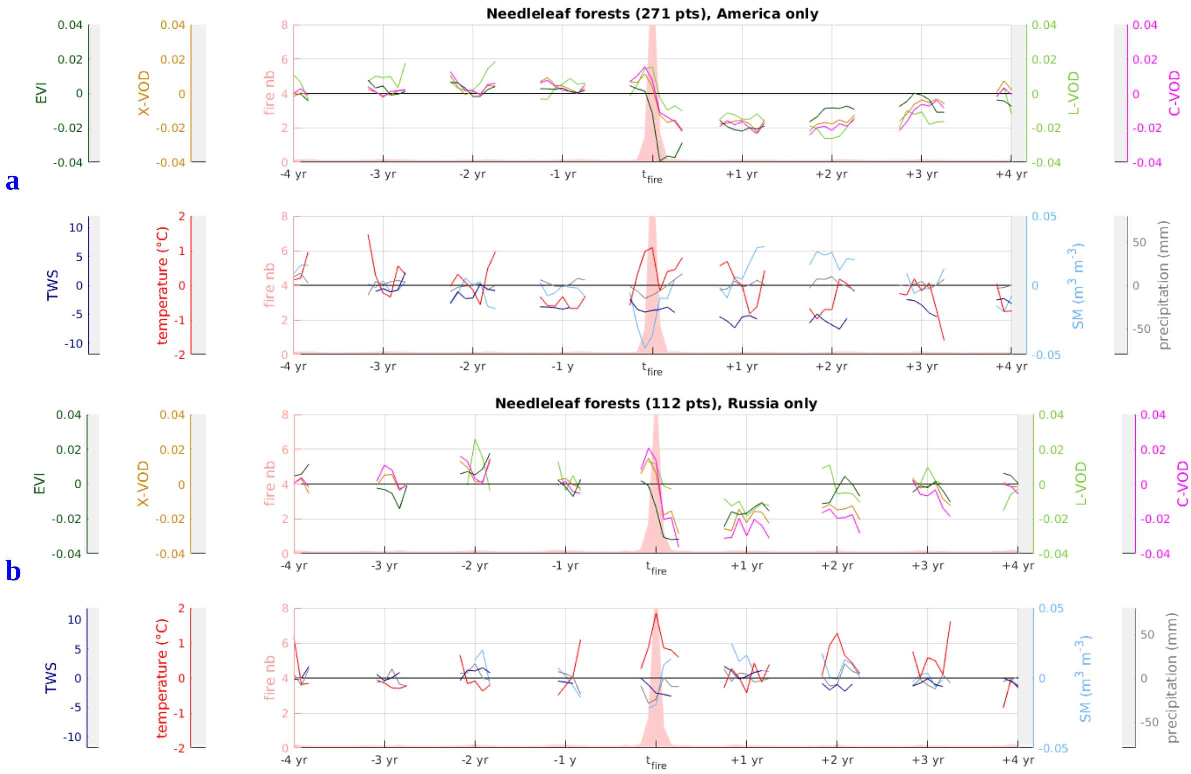

Figure R4 - Time series of the number of fires, and anomalies time series of EVI, X-, C-, L-VOD, P, SM, TWS, and T, shifted on the fire date, for a) American needleleaf forests and b) Eurasian needleleaf forests.

L 439: "It can be explained" – It is not clear to what "it" refers. I assume "it" refers to "L-VOD" from the previous sentence but then the sentence does not make sense. Please revise.
"It" refers to the whole previous sentence, "*We found that L-VOD is less impacted by fire than other VVs in this biome.*" The pronoun "This" is better adapted. The correction was made.

L 502-503: I doubt this statement as it is written. You come to this statement by averaging over many fire events from several continents but for most individual fires, it will be likely very hard to see an effect in L-VOD because most fires are much smaller than the spatial resolution of L-VOD. You need to revise the sentence in a way that it is specific to the results of your study.
The reviewer is right, the sentence was modified by: "*Thus, L-VOD seems the best adapted vegetation variable for the monitoring of dense vegetation recovery after wide fires.*"

Fig. 3: Some of the colours are almost impossible to see, especially the pale red and pale green of fires and L-VOD, respectively. What means "Fire nb" in the axis label?

In Fig. 3 and Fig. 5, we changed the pale red of fires by an orange colour; and the pale green of L-VOD by an intense green. Other colours were also modified for an enhanced visibility. An example is provided in Fig. R5 below. Please note that depending on your screen settings, colours may appear in a distorted way.
“Fire nb” means “number of fires”. We replaced it with “fires”.

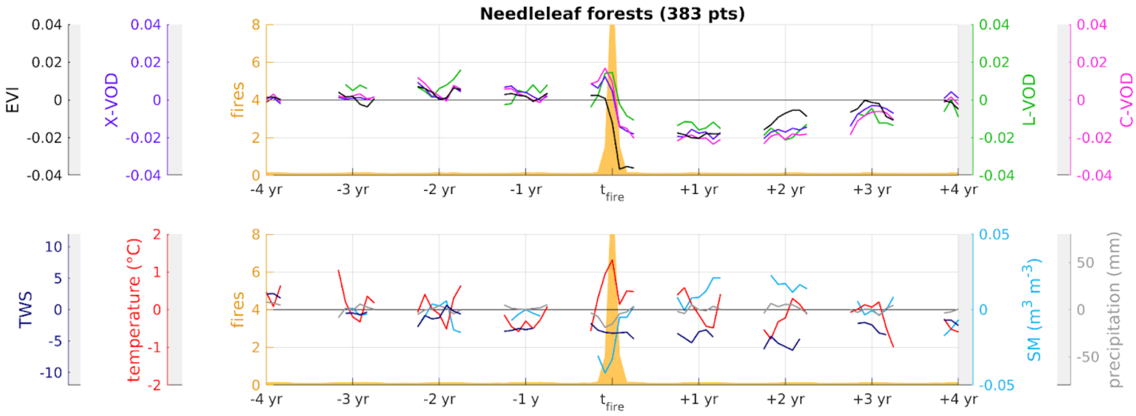

Figure R5 - Time series of the number of fires, and anomalies time series of EVI, X-, C-, L-VOD, P, SM, TWS, and T, shifted on the fire date, for the needleleaf forest biome, with new colours.

Fig. 4: The time series plots are too small and the labels are not sharp.
We increased the size of the time series plots according to your suggestion (Fig. R6).

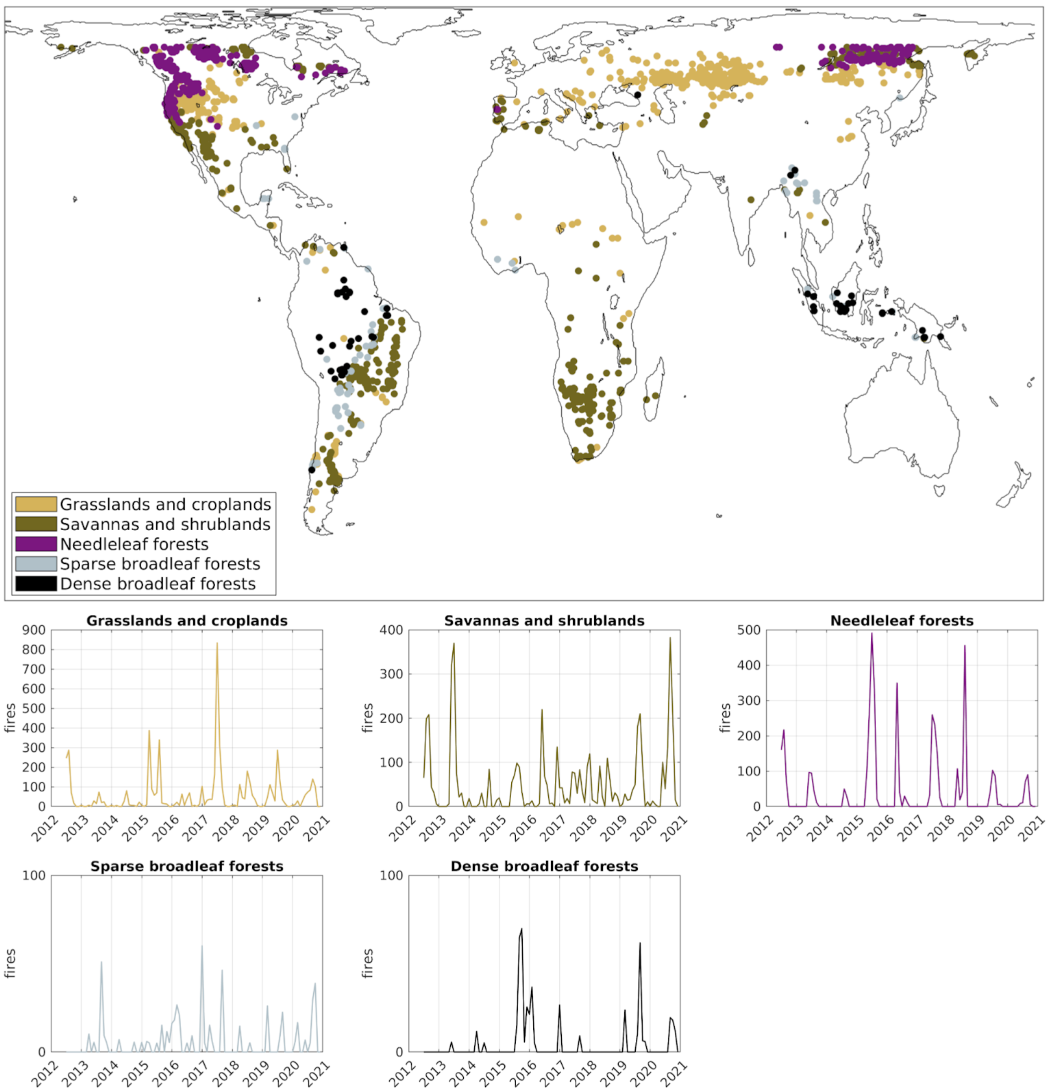

Figure R6 - Same as Fig. R2, modified for a better visibility.

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