APPENDIX 1

STANDARD COVER PAGE FOR ESA STUDY CONTRACT REPORTS

ESA STUDY CONTRACT REPORT – SPECIMEN

No ESA Study Contract Report will be accepted unless this sheet is inserted at the beginning of each volume of the Report.

ESA Contract No: 4000125441/18/I-NS	SUBJECT: The Living Planet Fellowship – Sentinel-1 for High Resolution monitoring of vegetation Dynamics (SHRED)	CONTRACTOR: TU Wien
* ESA CR( )No:	No. of Volumes: 1 This is Volume No: 1	CONTRACTOR'S REFERENCE: n.a.

ABSTRACT:
The objective of this project was to ***develop and use a novel high-resolution vegetation optical depth dataset based on ESA's Sentinel-1 satellites to improve our understanding on the local impacts of water availability on vegetation at a global scale using novel machine learning approaches***. This study has demonstrated that the Sentinel-1 backscatter ratio (VH/VV) is strongly related to vegetation optical depth (VOD) as observed from Metop ASCAT and passive microwave observations, and Copernicus Global Land Service Leaf Area Index over most land cover types. However, over deciduous forests the change in vegetation structure as a result of leaf out and fall affects backscatter to such an extent that CR does not capture dynamics which can be related to VOD. Similarly, over arid regions backscatter is affected by scattering from deeper soil layers when the signal has a higher penetration depth as a result of dry soils. These effects impede a reliable and physically sound retrieval of VOD from Sentinel-1.
Further detailed analysis were performed, demonstrating that VV backscatter has a strong relationship with soil moisture, VH shows a slightly stronger correspondence to LAI and CR is strongly related to LAI and FLUXNET gross primary production (GPP). Both Sentinel-1 VH and VV backscatter capture drought effects, where especially VH and VV backscatter show strong negative anomalies over northwestern Europe during the 2018 drought which correspond to anomalies found in surface soil moisture, LAI and GPP. CR however did not show any response to the 2018 drought.
The project demonstrates the value of Sentinel-1 for vegetation monitoring and its potential for drought monitoring. However, the results have demonstrated that the backscatter signal at the high resolution of Sentinel-1 can be strongly affected by vegetation structure and scattering affects from deeper soil layers. This shows that more fundamental research and field experiments need to be done to improve our understanding of scattering mechanisms at high resolution.
The project resulted in four published publications (1 first author) and two publications which are in preparation or in review (1 first author). It has also increased the collaboration between the fellow and TU Delft and has led to the involvement of the fellow in other national and international projects.

The work described in this report was done under ESA Contract. Responsibility for the contents resides in the author or organisation that prepared it.

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** NAME OF ESA STUDY MANAGER: DIV: DIRECTORATE:	** ESA BUDGET HEADING:

* Sections to be completed by ESA
** Information to be provided by ESA Study Manager

SHRED:

SENTINEL-1 FOR HIGH RESOLUTION MONITORING OF VEGETATION DYNAMICS

CARRIED OUT BY:

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ESA Living Planet Fellowship 4000125441/18/I-NS

CONTENTS

1 INTRODUCTION

Vegetation dynamics are controlled by climate drivers such as net radiation, water availability and temperature (Richardson et al., 2013). Trends and extremes in climate drivers can affect vegetation and impact for example the length of the growing season, productivity and mortality. But, through its role in the carbon-, energy-, and water- cycle vegetation also has feedbacks to climate, for example through evaporation-driven cooling in warm, arid regions (Forzieri et al., 2017) and cloud cover enhancement. In addition, changes in the timing of phenological events, such as the start of season, have been found to influence terrestrial carbon uptake and provide a negative feedback to the climate cycle through increased carbon uptake (Keenan et al., 2014).

Because of the crucial role of vegetation in the Earth system there is an urgent need to study the response of vegetation to a warming climate. This is also expressed by the World Climate Research Programme, who identified improving our understanding on **how highly vulnerable land carbon reservoirs will respond to a warming climate, climate extremes, and to abrupt changes** as one of their priorities. However, it is still poorly understood how climate extremes affect vegetation at the local scale. Especially, the **effects of water availability on vegetation dynamics and the subsequent feedbacks are still not fully understood**. Nevertheless, understanding these effects are essential since droughts are expected to become more frequent with global warming and demand of agricultural food production increases to ensure global food security. One challenge in investigating the response of vegetation to climate drivers at local scale is availability and accuracy of the data.

Compared to optical remote sensing, microwave remote sensing has the advantage of not being hindered by cloud cover, smoke and low solar illumination and can provide complementary information on the land surface in crucial areas with extensive cloud cover, such as the tropics and high latitudes. **Microwaves are sensitive to the structure and total water content in both the crown as well as the woody part of the vegetation**. A common microwave based parameter used to monitor vegetation is Vegetation Optical Depth, which parametrizes the attenuation of the microwave signal due to vegetation. The **low-resolution of the existing microwave-based VOD datasets has often been a limiting factor**, since it does not allow investigating local processes and differences between vegetation types while the signal is integrated over a large region. Since the launch of the Copernicus S1 series, backscatter data is available at a spatial and temporal resolution needed to monitor vegetation at local scale. The S1 satellites carry C-Band SARs, and the main sensing mode over land is the Interferometric Wide Swath Mode (IW), with a Ground Range Detected (GRD) resolution of 20m×22m at revisit frequency of 1.5-4 days over Europe. This provides for the first time the possibility to study vegetation dynamics with microwaves at high resolution. Studies have demonstrated the sensitivity of the VH/VV Cross Ratio (**CR**) to vegetation.

2 OBJECTIVES

The objective of this study was to ***DEVELOP AND USE A NOVEL HIGH-RESOLUTION VEGETATION OPTICAL DEPTH DA-TASET BASED ON ESA'S SENTINEL-1 SATELLITES TO IMPROVE OUR UNDERSTANDING ON THE LOCAL IMPACTS OF WATER AVAILABILITY ON VEGETATION AT A GLOBAL SCALE USING NOVEL MACHINE LEARNING APPROACHES***. To reach this objective I used Copernicus Sentinel-1 in combination with MetOp ASCAT VOD to 1) establish quantitative relationships between Sentinel-1 backscatter and ratios thereof and MetOp ASCAT VOD. The second planned step was to develop a high-resolution 1 km VOD product sensitive to changes in water content of the above ground biomass. The newly developed VOD were to be evaluated using different ESA and non-ESA EO datasets, among which are CGLS LAI and ESA's Earth Explorer SMOS VOD. Finally, the high-resolution VOD was to be used to quantify the effect of water availability on vegetation dynamics for different land cover types at the local scale. During the course of the project the approach has changed as the retrieval of VOD from Sentinel-1 with the proposed approaches was not possible in a reliable way. The new approach is described in the summary of work.

3 SUMMARY OF WORK

Data from Sentinel-1, Metop ASCAT, Copernicus Global Land Service Leaf Area Index and CCI Land Cover was collected. All data was resampled to the EQUI7 500m grid. The resampling of Sentinel-1 VH and VV data required the masking of outliers in the 10m resolution data. Several masking procedures were tested, to eliminate effects of e.g. cities and open water bodies. Furthermore, exceptionally low backscatter for certain orbits in S-1b were found and masked. Next, the CR was calculated from VH and VV data. Here, incidence angle normalization was performed through time series mean normalization.

The first analysis entailed a comparison between CR and VOD from Metop ASCAT and the long-term VODCA (VOD Climate Archive, Moesinger et al., 2020) to test the hypothesis that CR is sensitive to similar processes and parts of vegetation as VOD. Furthermore, the relation between if CR and VOD was quantified. Overall, high temporal correlation was found between CR and ASCAT VOD, especially over grass- and croplands. Over mixed and deciduous broadleaf forest negative correlations were found. Similar patterns were found with VODCA, although here also low correlations were found over bare soils and sparse vegetation. A linear regression analysis over Metop ASCAT pixels where the land cover was 80% homogenous showed similar results. Low correlation was found over deciduous broadleaf forest. This research was published in the first paper within SHRED and the abstract can be found in section 3.1.1.

This first analysis demonstrated that using CR to obtain VOD from Sentinel-1 is not straight forward and would require a high amount of exceptions and tweaking of data. As this would lead to a VOD product which might look good, but would not be robust and physically sound I decided to not continue on this path. Especially over deciduous forests the structure of vegetation can have a large effect on the CR, which leads to dynamics in CR that are related to leaf out and leaf fall, where CR decreases with increasing vegetation canopy. This would not relate the VOD as is used in the water-cloud or radiative transfer models, i.e the amount of attenuation of the signal due to water droplets in the vegetation. Furthermore, in very dry areas, where vegetation is non-existent or sparse, sub-surface scattering seems to affect the CR, where increasing penetration depth and subsurface rocks lead to higher volume scattering and thus higher CR. This was also demonstrated in a comparison between Copernicus Global Land Service Leaf Area Index and CR over Europe. Here low correlations are found over forests and dry areas (section 3.1.2). This analysis led to the conclusion that CR, and C-band backscatter in general, cannot be directly used to assess vegetation dynamics as is done with e.g. Leaf Area Index. The effect of structure, and soil contribution, over certain land cover types impedes the retrieval of VOD or to study vegetation dynamics.

Although VOD could not be retrieved from CR in a robust manner, I did assess the sensitivity of Sentinel-1 observables and the CR to inter-annual vegetation dynamics and to the drought of 2018 in particular. To do so monthly means and anomalies between 2018 and the reference year 2016 of VH, VV backscatter and CR were compared to Copernicus Global Land Service Leaf Area Index and GPP from FLUXNET stations. Results show that although VV and VH backscatter are sensitive to inter-annual variability and drought impact, the CR does not reflect drought impact. This study is described in detail in section 3.1.2.

The difficulty of interpreting the backscatter signal over deciduous forests and the effect of vegetation dynamics has motivated me to look in detail in the behaviour of backscatter and how it responds to different natural phenomena. First, the effect of leaf out and senescence over deciduous broadleaf forest with Metop ASCAT and Sentinel-1 was investigated. The first scientific paper on this was published by Pfeil et al. (2020), titled "Does ASCAT Observe the Spring Reactivation in Temperate Deciduous Broadleaf Forests?". To further investigate the effect of leaf out and senescence on Sentinel-1 a research proposal is submitted to the Austrian Science Fund. Further analyses within SHRED have focused on understanding the backscatter signal from both Sentinel-1 and Metop ASCAT over forests, and its relation to vegetation water dynamics. For a review article on detection bark beetle outbreaks in forests a thorough review was done of methods using radar (Hollaus and Vreugdenhil, 2019).

To improve our understanding of the sensitivity of active microwaves to vegetation water dynamics and drought, I worked together with Susan Steele-Dunne on an analysis over the Amazon region. Here we analysed backscatter, slope and curvature of the backscatter incidence angle relationship to meteorological data such as precipitation and radiation, and Equivalent Water Thickness from GRACE. Here, we found that slope and curvature dynamics vary considerably between evergreen forests and savannah regions. The evergreen forests show only small changes in slope and curvature, which follow changes in the radiation cycle. The Cerrado region showed a variety of dynamics in slope and curvature. Where the slope over croplands followed precipitation, over natural vegetation such as shrublands, herbaceous cover and forests, the slope was more related to radiation. More details on this work are in section 3.1.3.

3.1 PUBLICATIONS

Six publications on which I was first or co-author were published. The abstract of the published first author paper is in section 3.1.1. Furthermore, one first author paper is in preparation and in section 3.1.2.

Together with Markus Hollaus, I published a review paper on the use of Radar satellite imagery to detect bark beetle outbreaks in forests. I worked as co-author on two papers which all focused on the use of microwave observations to study vegetation dynamics over forests. First, I worked with my colleague Isabella Pfeil on the Metop ASCAT signal over temperate deciduous broadleaf forest to investigate if we can detect spring reactivation. Second, I worked intensively with Ashwini Petchiappan and Susan Steele-Dunne on detecting vegetation dynamics related to meteorological forcing and water availability on the Amazon forest using the slope of the backscatter incidence angle relationship. This paper was especially interesting as we looked at different land cover types and how slope is related to precipitation, vapour pressure deficit, radiation and total water storage. My work focused mainly on assessing slope dynamics over the highly heterogeneous Cerrado region. A third paper is submitted to Science of Remote Sensing by Isabella Greimeister-Pfeil: "Analysis of short-term soil moisture effects on the ASCAT backscatter-incidence angle dependence".

Vreugdenhil, M., C. Navacchi, B. Bauer-Marschallinger, S. Hahn, S. Steele-Dunne, I. Pfeil, W. Dorigo, and W. Wagner. 2020. 'Sentinel-1 Cross Ratio and Vegetation Optical Depth: A Comparison over Europe'. Remote Sensing 12 (20): 1–19. https://doi.org/10.3390/rs12203404.

Hollaus, M., and **M. Vreugdenhil**. 2019. 'Radar Satellite Imagery for Detecting Bark Beetle Outbreaks in Forests'. Current Forestry Reports 5 (4): 240–50. https://doi.org/10.1007/s40725-019-00098-z.

Petchiappan, A., S. C. Steele-Dunne, **M. Vreugdenhil**, S. Hahn, W. Wagner, and R. Oliveira. 2021. 'The Influence of Vegetation Water Dynamics on the ASCAT Backscatter-Incidence Angle Relationship in the Amazon'. Hydrology and Earth System Sciences Discussions, August, 1–29. https://doi.org/10.5194/hess-2021-406.

Reuß, F., Greimeister-Pfeil, I., **Vreugdenhil, M.**, Wagner, W., 2021. Comparison of Long Short-Term Memory Networks and Random Forest for Sentinel-1 Time Series Based Large Scale Crop Classification. Remote Sensing 13, 5000. https://doi.org/10.3390/rs13245000

Pfeil, I., W. Wagner, M. Forkel, W. Dorigo, and **M. Vreugdenhil**. 2020. 'Does ASCAT Observe the Spring Reactivation in Temperate Deciduous Broadleaf Forests?' Remote Sensing of Environment 250. https://doi.org/10.1016/j.rse.2020.112042.

Greimeister-Pfeil, I., W. Wagner, R. Quast, S. Hahn, S. Steele-Dunne, and **M. Vreugdenhil**. Science of Remote Sensing. 'Analysis of Short-Term Soil Moisture Effects on the ASCAT Backscatter-Incidence Angle Dependence'. Science of Remote Sensing, under review.

3.1.1 SENTINEL-1 CROSS RATIO AND VEGETATION OPTICAL DEPTH: A COMPARISON OVER EUROPE[1]

Vegetation products based on microwave remote sensing observations, such as Vegetation Optical Depth (VOD), are increasingly used in a variety of applications. One disadvantage is the often coarse spatial resolution of tens of kilometers of products retrieved from microwave observations from spaceborne radiometers and scatterometers. This can potentially be overcome by using new high-resolution Synthetic Aperture Radar (SAR) observations from Sentinel-1. However, the sensitivity of Sentinel-1 backscatter to vegetation dynamics, or its use in radiative transfer models, such as the water cloud model, has only been tested at field to regional scale. In this study, we compared the cross-polarization ratio (CR) to vegetation dynamics as observed in microwave-based Vegetation Optical Depth from coarse-scale satellites over Europe. CR was obtained from Sentinel-1 VH and VV backscatter observations at 500 m sampling and resampled to the spatial resolution of VOD from the Advanced SCATterometer (ASCAT) on-board the Metop satellite series. Spatial patterns between median CR and ASCAT VOD correspond to each other and to vegetation patterns over Europe. Analysis of temporal correlation between CR and ASCAT VOD shows that high Pearson correlation coefficients (R_p) are found over croplands and grasslands (median $R_p > 0.75$). Over deciduous broadleaf forests, negative correlations are found. This is attributed to the effect of structural changes in the vegetation canopy which affect CR and ASCAT VOD in different ways. Additional analysis comparing CR to passive microwave-based VOD shows similar effects in deciduous broadleaf forests and high correlations over crop- and grasslands. Though the relationship between CR and VOD over deciduous forests is unclear, results suggest that CR is useful for monitoring vegetation dynamics over crop- and grassland and a potential path to high-resolution VOD.

3.1.2 SENSITIVITY OF SENTINEL-1 BACKSCATTER OBSERVABLES TO DROUGTH IMPACT ON VEGETATION

3.1.2.1 INTRODUCTION

With the Copernicus Sentinel-1 series, for the first time high temporal and spatial resolution backscatter time series have become available. Sentinel-1 backscatter observations are sensitive to changes in water content and structural changes in vegetation and soils and provide complementary information next to optical remote sensing datasets such as Leaf Area Index. However, most studies have looked at the sensitivity of Sentinel-1 backscatter to vegetation water dynamics at local scale (Khabbazan et al., 2019, Vreugdenhil et al., 2018, Veloso et al., 2018). These studies demonstrate the capability to monitor vegetation dynamics with Sentinel-1. However, these studies also demonstrated that vegetation structure can have a large impact on backscatter. Furthermore, no specific focus has yet been on assessing anomalies in Sentinel-1 backscatter and monitoring drought impact on vegetation.

With the changing climate, droughts are expected to increase in frequency and intensity. The record summer drought of 2018 was characterized by higher temperatures and consistent dry period from June to November over north-western Europe. From late spring to autumn temperatures were more than 1°C above average. Negative precipitation anomalies were observed in northern Europe, whereas southern Europe received more precipitation than average. Subsequently, low soil moisture conditions were observed over northern Europe, where autumn, and 2018 on average showed the lowest soil moisture conditions in 40 years. The drought also had an impact on vegetation, with low crop yields. Reinermann et al. (2020) used MODIS Enhanced Vegetation Index (EVI) to assess the impact of the 2018 drought on vegetation in Germany, and

[1] https://www.mdpi.com/2072-4292/12/20/3404

found that vegetation development was mainly affected during summer months and mainly in grass- and croplands. Burras et al. (2020) found that pastures and croplands were more sensitive to the climatic water balance and were negatively impacted by the 2018 drought. Similar results were found in studies using flux tower and EO-based upscaled Gross Primary Production (GPP) to assess the impact of the 2018 European drought. Fu et al. (2020) found varying response between vegetation types, where grasslands showed a stronger decrease in GPP than forests. Bastos et al., (2020) demonstrated that FLUXCOM GPP in areas with high forest cover was higher than usual during drought conditions, whereas areas with high crop cover showed strong negative anomalies in GPP. Bastos et al., (2020) also found that land CO_2 increased or stayed neutral at the annual scale, as increased uptake in spring compensated for decreased activity in summer. The increased vegetation activity in spring was also found by Reinermann et al. (2020).

The aim of this study is to assess the potential of Sentinel-1 backscatter and ratios thereof to monitor vegetation and particularly the impact of drought on vegetation. The 2018 drought is taken as a case study to analyse in detail the response of Sentinel-1 backscatter and ratios to the drought for different vegetation types. This study goes beyond the state-of-the-art as it is the first study to perform a large scale analysis of Sentinel-1 backscatter sensitivity to vegetation dynamics from both optical data and flux tower (FLUXNET) based GPP. Also, it is the first study to assess the potential of Sentinel-1 to assess drought impact.

3.1.2.2 DATA AND METHODS

3.1.2.2.1 CONTINENTAL SCALE

This study was performed both at a continental scale, as well as local scale for the FLUXNET sites. All available Sentinel-1 IWGRDH backscatter data was collected over Europe for the period 2016-2019 and pre-processed and resampled to the 500m EQUI7Grid in the same manner as done by Vreugdenhil et al. (2020). The Cross Ratio of VH and VV backscatter was calculated in the linear domain as VH/VV. For the same spatial and temporal extent Copernicus Global Land Service Leaf Area Index data at 300m was resampled to the 500m EQUI7Grid. The Sentinel-1 observables and LAI were masked for frozen soils (T<2°C) and snow cover (snow water equivalent > 0.05mm) using ERA5-Land model data. LAI, backscatter and CR are aggregated to monthly values using an arithmetic mean. ESA CCI Land Cover (2015) was resampled to the 500m EQUI7Grid to analyse results per land cover type. The sensitivity of backscatter and CR to vegetation dynamics is assessed at the continental scale through a temporal correlation analysis with CGLS LAI and ESA C3S surface soil moisture.

C3S surface soil moisture (passive product only) time series were used, aggregated to monthly means and resampled to the 500m EQUI7Grid. From the time series anomalies were calculated based on the long-term climatology. To enable a fair comparison in drought conditions in space, a drought indicator was calculated using the percentiles of the monthly long-term mean (1978-2020). Five percentile bins were selected [0, 0.1, 0.33, 0.66, 0.9, 1], leading to severe drought, moderate drought, normal conditions, wet conditions, very wet conditions.

At the continental scale, backscatter data was masked for pixels which showed a negative correlation coefficient between LAI and CR based on the temporal correlation analysis. The anomalies of LAI, VV, VH and CR were calculated in % change for 2018 using 2016 as a reference (i.e. (2018-2016)/2016). The monthly anomalies are analysed with regard to the drought indicator from passive microwave soil moisture data and ESA CCI land cover. At the local scale a detailed analysis is performed on dynamics in backscatter and CR and their relation to Gross Primary Production data (GPP) and Soil Water Content (SWC). GPP and SWC data were extracted from the Integrated Carbon Observation System (ICOS) FLUXNET stations over Europe. All results are analysed with respect to land cover type as provided by the FLUXNET stations. Second, anomalies of backscatter and CR are analysed with respect to GPP.

3.1.2.3 RESULTS AND DISCUSSION

3.1.2.3.1 BACKSCATTER SENSITIVITY TO VEGETATION AND SOIL MOISTURE DYNAMICS

Figure 1 shows the spatial maps of the temporal correlation analysis between Sentinel-1 observables and CGLS LAI and CCI SSM for the period 2016-2019. Figure 2 shows the correlation coefficients per land cover class. Positive correlations are found between CR and LAI over most regions. Especially high correlations are found over croplands and grasslands, with median R_s >0.7. R_s decreases for croplands with increasing herbaceous or tree cover. Striking patterns are found, where strong negative correlations are found over

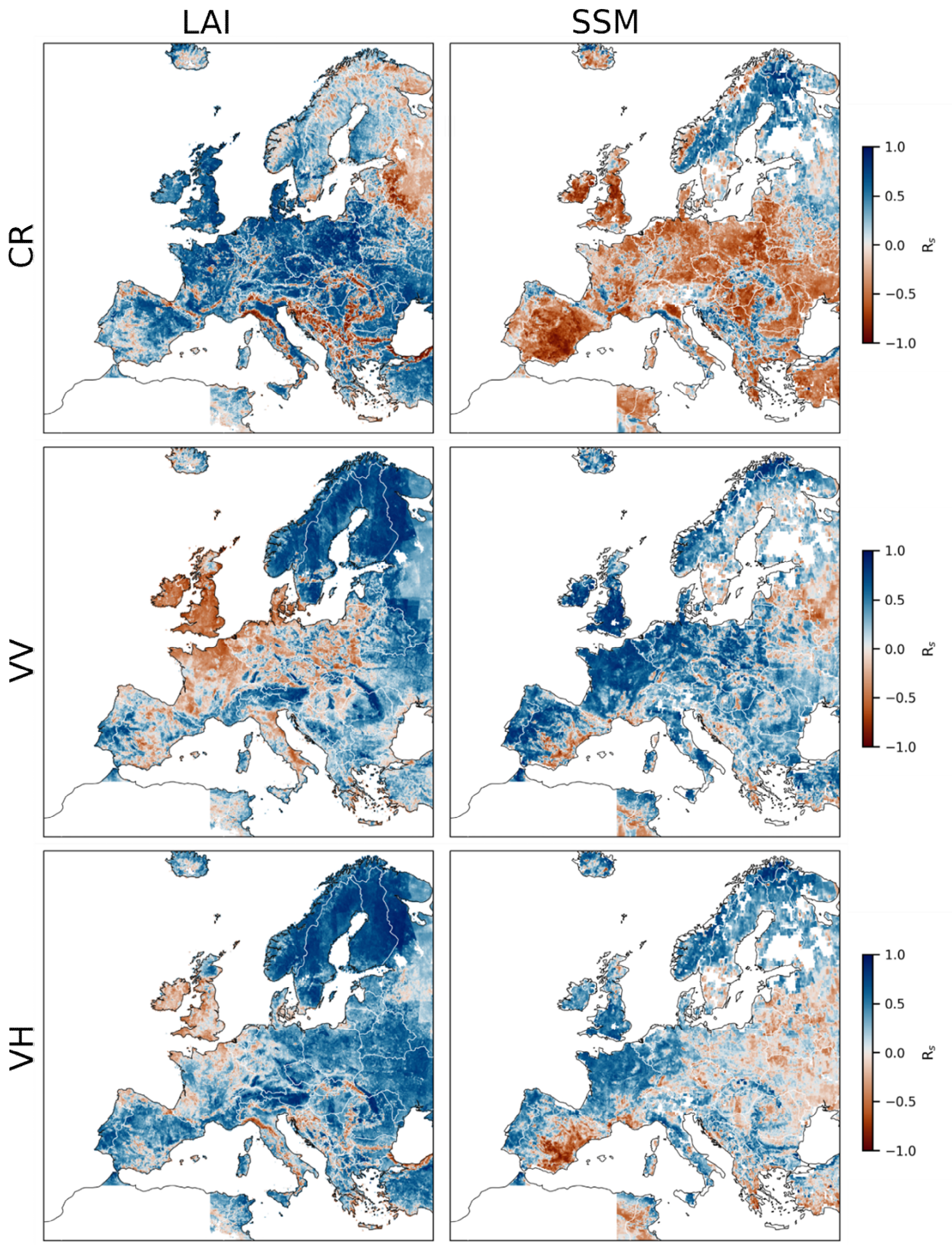

Figure 1: Spatial map and boxplot per CCI Land Cover class for Pearson correlation coefficient between CR, VV and VH with CGLS LAI and ESA CCI SSM.

well-known forest areas in Europe. For broadleaved deciduous forest (Tree cover, BD in Figure 2) strong negative correlations are found, where BD forest with >40% tree cover have lower correlations than those with >15% tree cover. This indicates that with increasing tree density the backscatter signal start to behave increasingly different compared to LAI. The anticyclical behaviour of CR is likely caused by strong changes in structure as a result of leaf out and leaf fall and explained in more detail in the next section. Needleleaf evergreen forest (Tree cover, NE) show low correlations, also with lower correlations for more densely forested pixels. For NE forests however, a large range of correlation coefficients is found, and more positive correlations are found then for deciduous forests. Many NE forests are in areas where radar has difficulty obtaining a reliable signal, such as areas with snow cover, frozen soils, steep terrain and open water. Therefore, the range of correlation coefficients between CR and LAI varies strongly, with more negative correlation in e.g. Scandinavia and Alps. Also for mixed forest negative correlations are found, with the median between that of NE and BD forest. In shrublands and sparsely vegetated areas the correlation between CR and LAI varies and the median is often close to 0. Some of these regions are located in Spain, where low correlations are found in the inland area. This could be because of subsurface scattering, which was found by Morrison and Wagner (2020). When the soil is exceptionally dry, the microwave signal can penetrate into the surface. When rocks or bedrock is located close under the surface, this can increase depolarization, leading to an increase in volume scattering and consequently an increase in CR. This may lead to lower correlations with LAI, as in these regions it is expected that vegetation is water limited, and thus would decrease during dry soil moisture conditions. CR is negatively correlated to C3S SSM over most regions, especially in central and southern Europe. Over northern Europe and BD forest more positive correlations are found. However, note that over deciduous forests the signal is affected by leaf fall and leaf out.

VV backscatter is predominantly negatively correlated to LAI, and strongly correlated to soil moisture as expected. However, in northern regions, over NE forest and sparse vegetation VV is also strongly related to LAI. Sensitivity to soil moisture in VV backscatter is lower over NE forest as the signal most likely does not

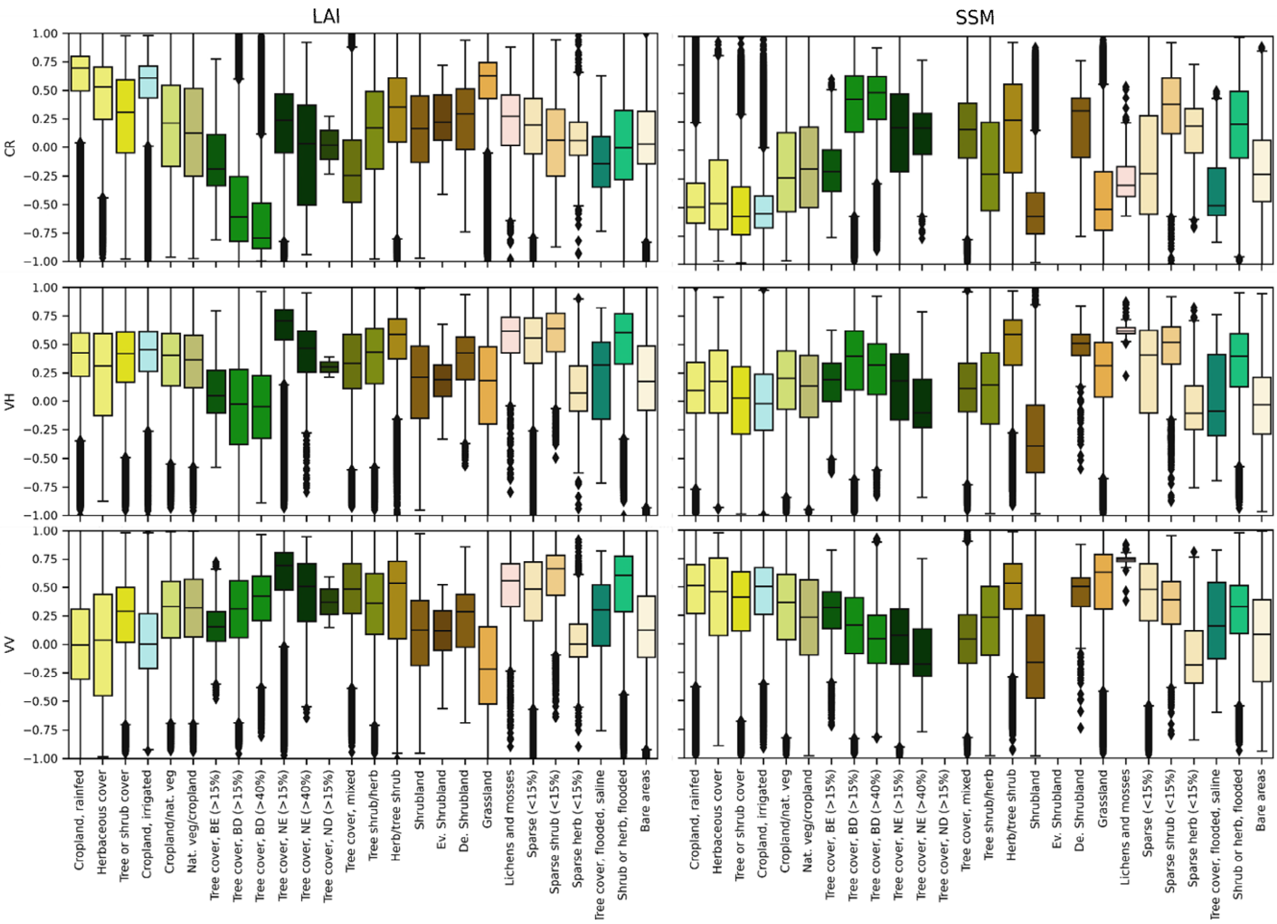

Figure 2: Boxplots of correlation coefficients between CR, VV and VH with LAI and SSM per land cover class.

penetrate the vegetation. Negative correlations are observed between VV and soil moisture over some regions in southern Europe and is mainly in shrublands. This is likely related to subsurface scattering, where increasing roughness or bedrock is increasing VV backscatter when soil is actually at its driest. VH backscatter shows medium to strong correspondence to LAI over NE forests and sparse vegetation types. Over all other land cover classes correlations with LAI are low to medium (median $R_s < 0.5$). Similarly, correlations with soil moisture are lower than for LAI, often low to medium. Interestingly, over Spain, the regions where correlation with soil moisture is negative, is in the same region as for VV, but for a larger spatial extent.

Over the 42 FLUXNET sites the same behaviour is found and the correlation coefficients between Sentinel-1 observables and GPP, LAI and soil moisture are shown in **Error! Reference source not found.**. Over crop- and grasslands strong positive correlations are found between CR and LAI and GPP and negative correlations are found with soil moisture. VV and VH backscatter show the opposite behaviour for crop- and grassland with low to negative correlations to GPP and LAI and high correlations with soil moisture. VV shows the strongest relation to surface soil moisture, which is expected from the sensitivity of VV to surface scattering. For BD and mixed forest (DBF, EBF and MF in figure 3) there are low correlations between the vegetation datasets, but high correlations for VV and VH with soil moisture. Over NE forest (ENF in figure 3) correlations between CR, GPP and LAI vary strongly, and correlation with soil moisture is lowest for CR. For VV and VH low correlations with soil moisture and higher correlations with GPP and LAI are found over NE forest. The results of the FLUXNET analysis confirm the results found at European scale. With high correspondence between CR and vegetation indicators over all land cover types except deciduous forests. And high correspondence between backscatter and soil moisture over most land cover types except forests.

Figure 4 shows four time series of CR, LAI and GPP (top figures) and VV and VH backscatter with soil moisture if available. These sites were chosen as they demonstrated exemplary behaviour for cropland, grassland, savannah and deciduous forest, where land cover is based on data from the ICOS station. Over crop- and grasslands there is a strong correspondence between CR and GPP and LAI ($R_{s,GPP}$ =0.76 and $R_{s,LAI}$=0.71 for cropland and $R_{s,GPP}$ =0.67 and $R_{s,LAI}$=0.78 for grassland respectively). VV backscatter corresponds with soil moisture over the cropland site with R_s=0.53, whereas VH is not strongly related to soil moisture. Over savannah regions a different behaviour is seen, where CR corresponds to GPP and LAI at the beginning of the growing season. However, when GPP and LAI start to decrease, the CR stays high. This is reflected in the low correlation coefficients with low correspondence to GPP ($R_{s,GPP}$=0.17) and medium correspondence to LAI ($R_{s,LAI}$=0.52). Also VH and VV seem to increase or stay stable even soil moisture is decreasing, although VV backscatter does show a high correlation to soil moisture (R_s=0.71). This behaviour of backscatter and CR is most likely the result of volume scattering from the subsurface. When the soil becomes very dry the signal penetrates deeper into the soil, leading to increased volume scattering as a result of penetration depth or because of a rough surface in the subsurface. This behaviour was also found by Morrison and Wagner (2020) using tomographic profiling in a laboratory investigation, where cross-polarized returns were strongly

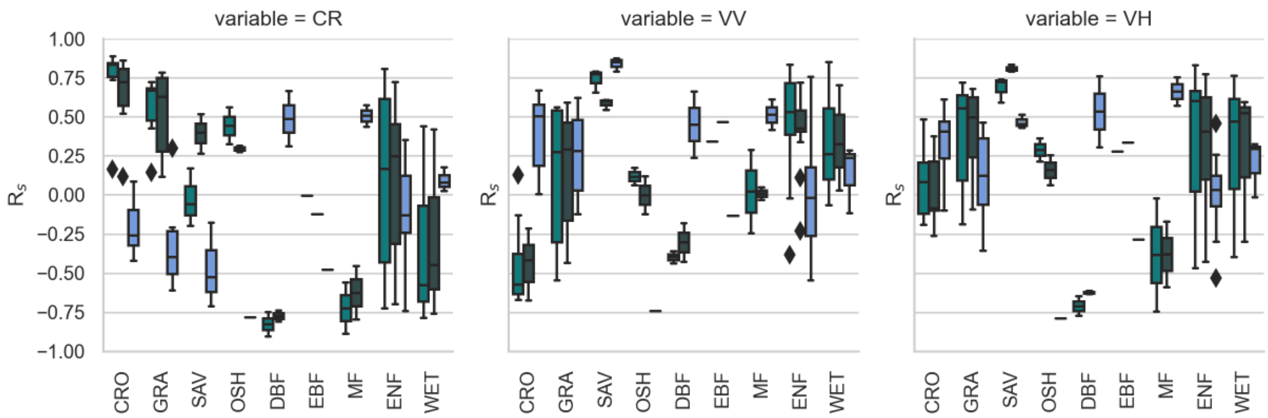

Figure 3: boxplots of correlation between CR, VV, VH with LAI, GPP and soil moisture from ICOS stations. The legend is the same as Figure 4, LAI (green), GPP (darkgreen), soil moisture (blue).

affected by the subsurface and co-polarized returns were originating from the surface or subsurface depending on soil moisture conditions. The results here show that this effect can also be observed in natural environments with Sentinel-1 leading to uncertainties in retrieval of soil moisture and vegetation.

Over BD forest there is an inverse behaviour in CR, where CR starts to decrease when GPP and LAI increase at the beginning of the growing season and vice versa during senescence leading to negative correlations ($R_{s,GPP}$=-0.90, $R_{s,LAI}$=-0.81). This also clearly seen in the VH signal, which decreases at the start of the growing

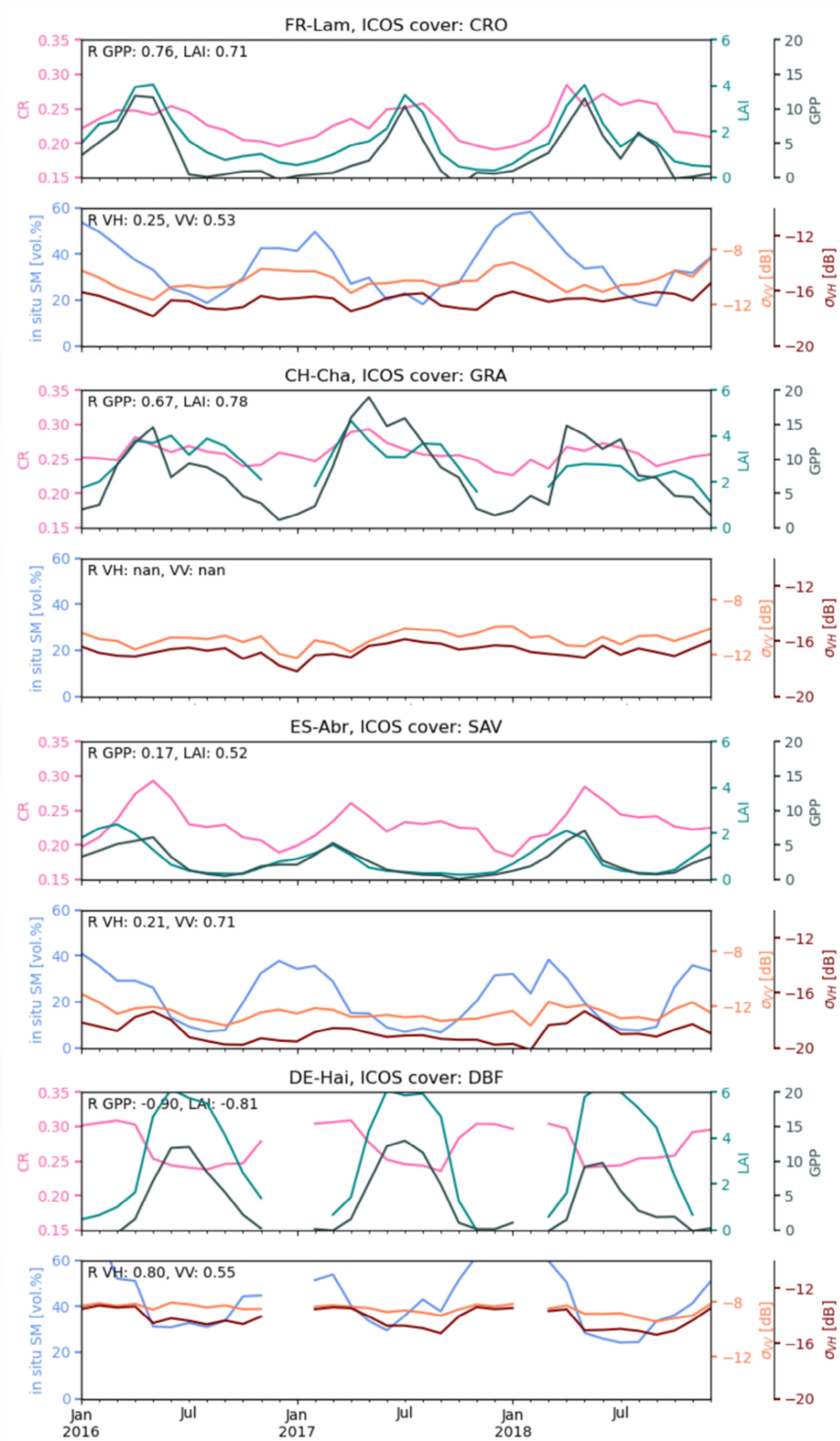

Figure 4: time series of S1 CR, GPP and LAI, and VH, VV and soil moisture for four exemplary ICOS sites from top to bottom: cropland, grass-land, savanna and deciduous forest.

season. Similar behaviour for VH was found by numerous studies on forest mapping and deriving phenology from Sentinel-1. Dostalova et al. (2021) use the behaviour of VH to map between deciduous forest and evergreen needleleaf forests. Also Ruetschi et al. (2018) found this striking seasonal signature of VH in deciduous forests. Deciduous forests are characterized by their strong seasonality in leaf out and senescence. The presence and absence of leafs has a strong influence on the structure of the vegetation and this is changing the scattering mechanism and affecting the backscatter signal. Ruetschi et al. (2018) suggest that C-band radar is mainly sensitive to small twigs and branches, and that this signal is attenuated when leafs come out, leading to a lower backscatter. A second hypothesis suggested by Ruetschi et al. (2018) is that during leaf-off periods the ground backscatter has a higher contribution as it is not attenuated by the leafs. In general, they hypothesize that leaf-out causes more volume scattering, thus affecting VH stronger than VV. Here it can also be observed that VH decreases strongly, but VV increases in 2016 and decreases only slightly in 2017 and 2018. As the decrease in VH backscatter coincides with the decrease in soil moisture in summer in Germany, high correlations are found between VH backscatter and soil moisture (R_s=0.80).

3.1.2.3.2 BACKSCATTER SENSITIVITY TO DROUGHT

Figure 5 show the spatial maps of the anomalies between 2018 and 2016 for CGLS LAI, CR, VV, VH and C3S soil moisture percentiles for 2018 for the period March, April, May and June, July, August. **Error! Reference source not found.** shows the anomalies between 2016 and 2018 for different land over types over pixels where the soil moisture indicates a severe drought in summer (SSMDI<2).

Sentinel-1 backscatter, both VV and VH, show positive anomalies for spring 2018. Weak to strong negative anomalies (5 to 30 %) can be observed in CR and LAI over southern and eastern regions in Europe. Positive anomalies are found in northern Europe, although negative anomalies are already occurring in Germany and the Netherlands. Looking at the anomalies per land cover class, LAI shows positive anomalies over all land cover classes except rainfed cropland, with the strongest increase around 20% over forests. This higher productivity was also found by Smith et al. (2020) and Bastos et al. (2020) investigating LAI, CO_2 and GPP response to the 2018 drought. Forests likely benefit from higher temperatures and radiation in spring 2018, whereas croplands might already be affected by decreasing soil water availability. Note that VV and VH show a strong increased backscatter in croplands in spring, whereas CR shows lower values compared to 2016. Over forests there are no clear differences in CR, VH and VV between 2016 and 2018, although a small negative anomaly in backscatter can be observed in BD forest. Leaf out occurs during this period over most of Europe, and as the change in vegetation structure is affecting the signal, the timing of leaf out may have

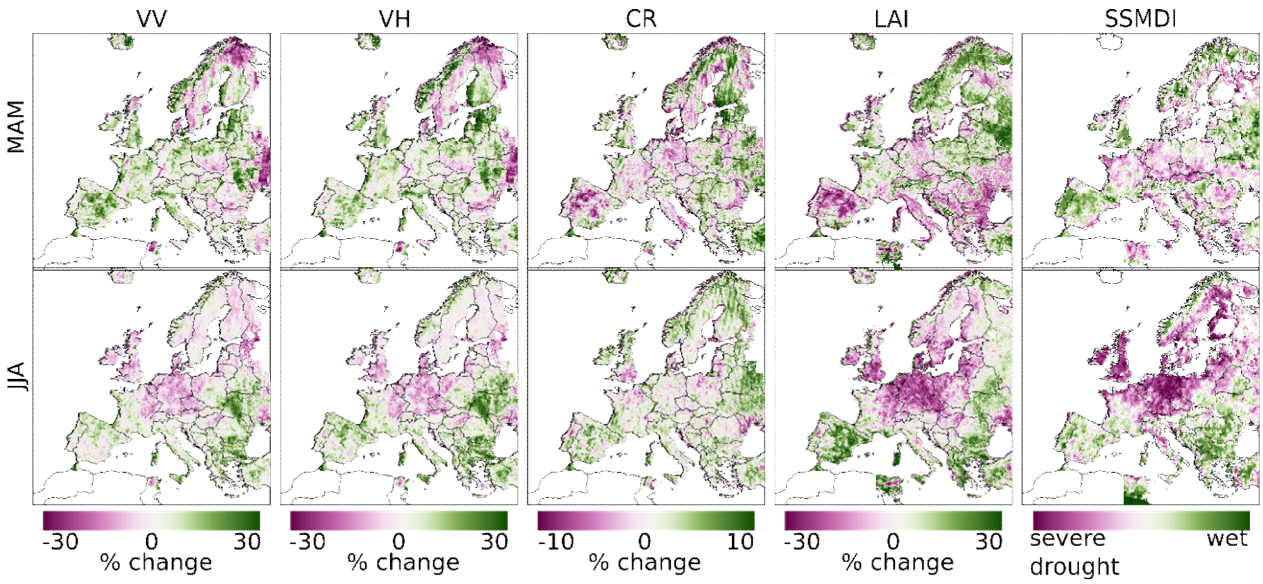

Figure 5: Anomalies between 2016 and 2018 for VV, VH, CR, LAI and SSMDI for March, April, May and June, July, August.

an effect. For example, if leaf out is earlier, this would lead to lower backscatter values earlier in the season decreasing the mean backscatter for the period.

Very strong negative anomalies in VV and VH can be observed during summer months over central and north-western Europe, similar to those observed in LAI and in soil moisture (Figure 5). Schuldt et al. (2020) found a profound stress response in forests over Germany, Switzerland and Austria, with widespread discoloration and low NDVI values. Similarly, Reinermann et al. (2019) found strong negative anomalies in the Enhanced Vegetation Index in Germany. Figure 5 does show that especially over these regions negative anomalies in LAI, VV and VH can be observed. LAI , VV and VH show very similar anomalies per land cover type for the summer period (Figure 6). With negative anomalies over most land cover classes in summer, except irrigated croplands and shrublands. These two land cover types most likely benefit from the higher amount of radiation and temperature during a drought. Most affected are crop- and grassland, with strong anomalies in LAI, VV and VH. This can be explained by their shallower rooting depth making them more sensitive to water deficits. Smaller negative anomalies are found over forests. The strong impact of drought over crop- and grasslands, and the lower impact over forests was also found by Burras et al. (2020), Bastos et al. (2020)

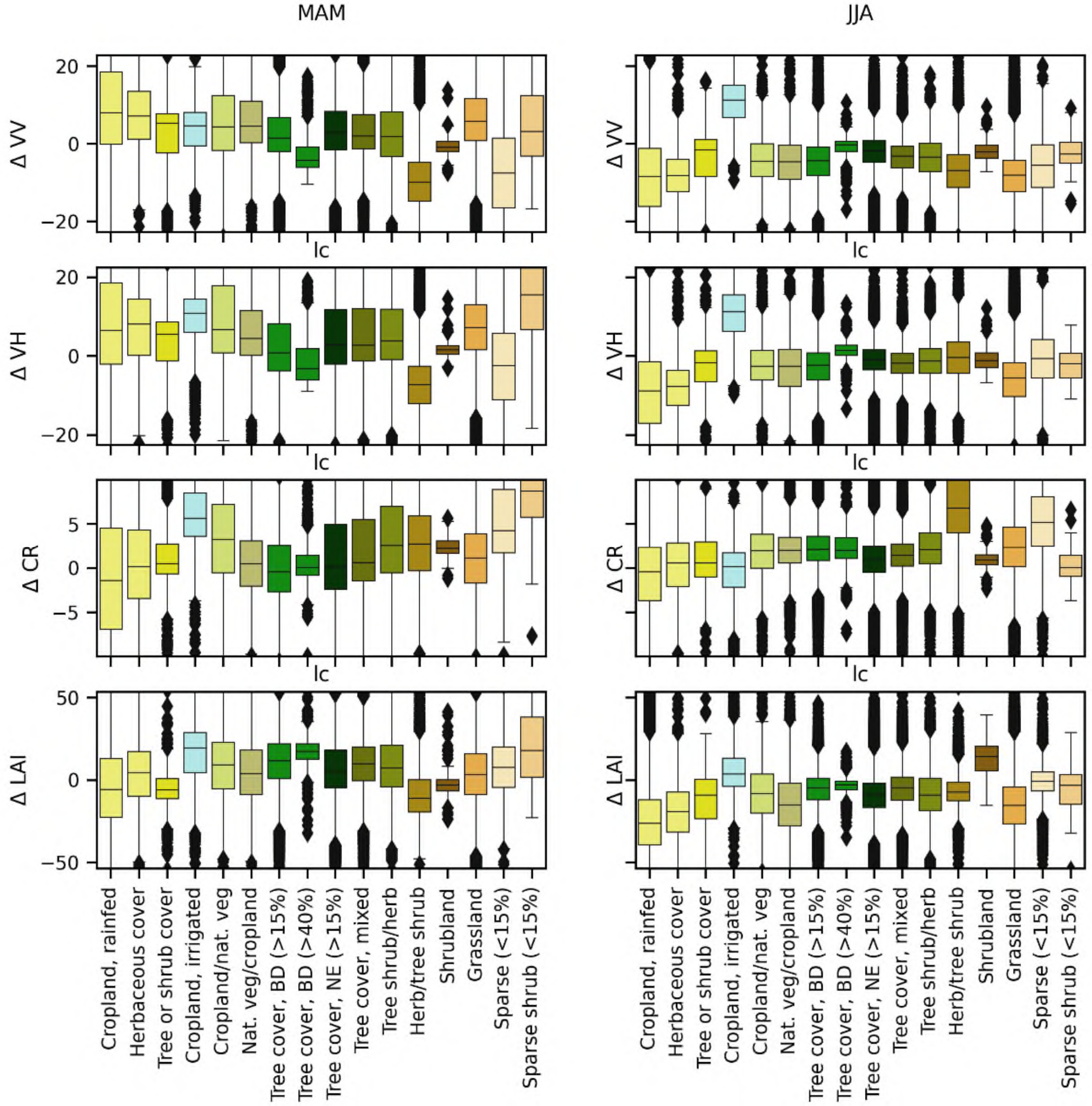

Figure 6: Anomalies for VH and VV backscatter, CR and LAI per land cover class for spring (MAM) and summer (JJA) for regions where the C3S SSMDI=-2.

and Fu et al. (2020) using NDVI, in situ and modelled GPP. Burras et al. (2020) suggested that forests have a higher climatic buffering function due to the microclimate in forests and the deeper rooting depth. Bastos et al. (2020) showed that with increasing crop cover within a pixel stronger negative GPP were found. Very similar results are found here for VH and VV backscatter. From section 3.1.2.3.1 it can be assumed VV is more sensitive to soil moisture dynamics, and VH more to vegetation dynamics. Anomalies in both LAI and SSM show a very similar spatial pattern, with the strongest negative anomalies over Germany. However, these anomalies are not at all represented in CR. Although Vreugdenhil et al. (2018) suggested CR might be sensitive to inter-annual variations in crop development, the results from this study show that this is not obvious for the 2018 drought. As both VV and VH show strong negative anomalies, this may explain why the ratio of the two, the CR, does not reflect any impact of the drought and stays relatively stable. Comparing CR to FLUXNET GPP it is clear that CR does not capture anomalies as observed in GPP (Figure 7). Where GPP shows positive anomalies in spring (MAM) and negative anomalies in summer in north western Europe, this is not represented in CR.

3.1.2.4 CONCLUSION

This study investigated the sensitivity of Sentinel-backscatter and CR to vegetation and soil moisture dynamics and particularly the potential of Sentinel-1 to monitor drought impact on vegetation. Results show that CR is most sensitive to vegetation phenology as observed in LAI over most land cover types except for deciduous broadleaf forest. This is attributed to the large changes in vegetation structure as a result of leaf out and leaf fall, changing the scattering mechanism. CR is negatively correlated to soil moisture over most land cover types, except deciduous broadleaf forest, although this is a result of the structural changes in vegetation. VV backscatter is more sensitive to soil moisture dynamics, but this sensitivity decreases for forests. Over dry regions, both CR and VV backscatter are affected by subsurface scattering, where subsurface scattering increases CR and VV during dry soil moisture conditions. VH backscatter is more sensitive than CR to LAI over deciduous broadleaf forests. CR shows a similar seasonal trajectory as GPP measured over FLUXNET sites for crop- and grasslands. Over deciduous forest there is a clear decrease in CR, VH and VV backscatter when the growing season for trees starts and GPP increases. In arid regions CR represents vegetation dynamics, as VV represents soil moisture dynamics, but both start to deviate during dry season. Where GPP and soil moisture decrease, CR and VV stay at a high level. This is, as mentioned, likely the result of scattering from the subsurface, either as volume scattering or on a rough subsurface.

Although this study, demonstrated that CR is sensitive to vegetation phenology, it does not show any negative anomalies during the 2018 drought. VH and VV backscatter do capture inter-annual variability and show strong negative anomalies in 2018 with same spatial patterns as LAI and soil moisture demonstrating that Sentinel-1 VV and VH backscatter can be used to monitor drought impact. However, challenges remain in interpreting VV or VH backscatter response as there is a strong coupling between soil moisture and vegetation response making it difficult to separate the impact of low soil moisture or low vegetation productivity on the VV and VH. This study suggests, that although CR is sensitive to vegetation phenology during the year over most land cover types, as was demonstrated by an extensive validation with LAI and GPP, it is not suitable for detecting inter-annual variability. Note that this study compared two years, 2018 to the reference of 2016. When longer time series of Sentinel-1 backscatter are available a comparison to a long-term climatology needs to be performed. The results demonstrate that our understanding of radar observables still needs to be improved, particularly over forests and arid regions, and that ratios of backscatter need to be treated with care.

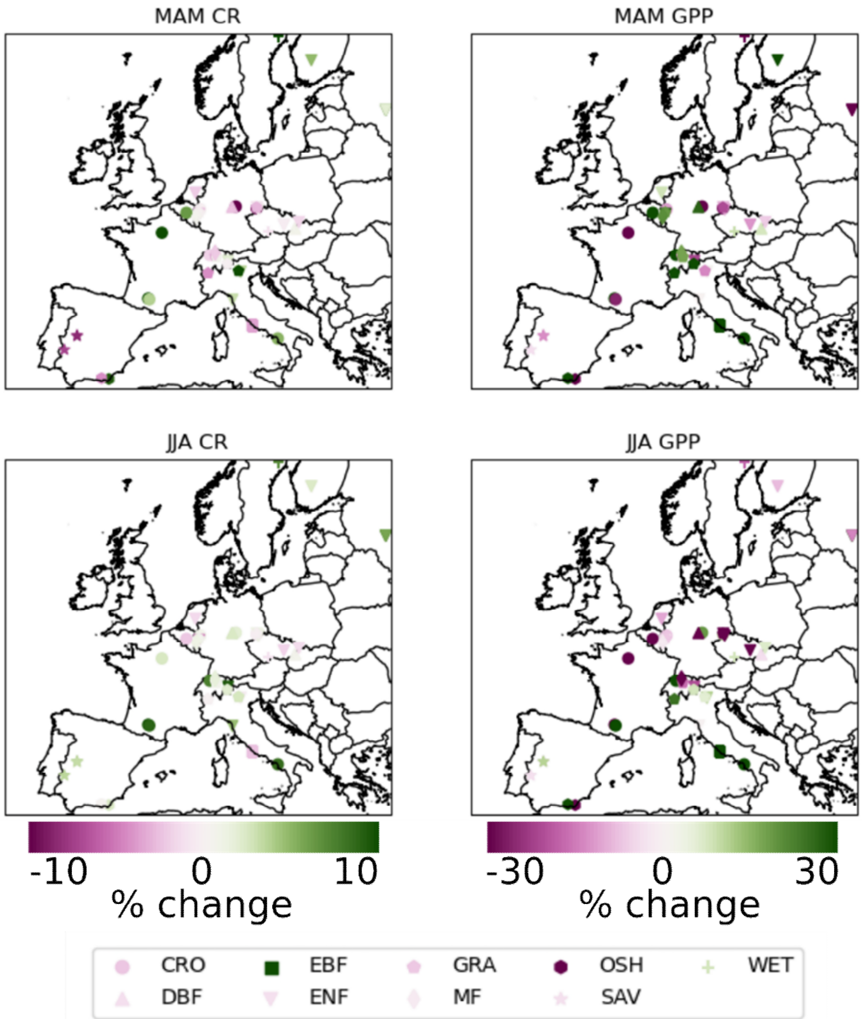

Figure 7: Anomalies in percent change between 2016 and 2018 for MAM and GPP over FLUXNET sites, for CR and GPP.

3.1.3 THE INFLUENCE OF VEGETATION WATER DYNAMICS ON THE ASCAT BACKSCATTER-INCIDENCE ANGLE RELATIONSHIP IN THE AMAZON[2]

Microwave observations are sensitive to plant water content and could therefore provide essential information on biomass and plant water status in ecological and agricultural applications. The combined data record of the C-band scatterometers on ERS 1/2, the Metop series and the planned Metop Second Generation satellites will span over 40 years, which would provide a long-term perspective on the role of vegetation in the climate system. Recent research has indicated that the unique viewing geometry of ASCAT could be exploited to observe vegetation water dynamics. The incidence angle dependence of backscatter can be described with a second order polynomial, the slope and curvature of which are related to vegetation. In a study limited to grasslands, seasonal cycles, spatial patterns and interannual variability in the slope and curvature were found to vary among grassland types and were attributed to differences in moisture availability, growing season length and phenological changes. To exploit ASCAT slope and curvature for global vegetation monitoring, their dynamics over a wider range of vegetation types needs to be quantified and explained in terms of vegetation water dynamics. Here, we compare ASCAT data with meteorological data and GRACE Equivalent Water Thickness (EWT) to explain the dynamics of ASCAT backscatter, slope and

[2] https://hess.copernicus.org/preprints/hess-2021-406/

curvature in terms of moisture availability and demand. We consider differences in the seasonal cycle, diurnal differences, and the response to the 2010 and 2015 droughts across ecoregions in the Amazon basin and surroundings. Results show that spatial and temporal patterns in backscatter reflect moisture availability indicated by GRACE EWT. Slope and curvature dynamics vary considerably among the ecoregions. The evergreen forests, often used as a calibration target, exhibit very stable behaviour even under drought conditions. The limited seasonal variation follows changes in the radiation cycle, and may indicate phenological changes such as litterfall. In contrast, the diversity of land cover types within the Cerrado region results in considerable heterogeneity in terms of the seasonal cycle and the influence of drought on both slope and curvature. Seasonal flooding in forest and savanna areas also produced a distinctive signature in terms of the backscatter as a function of incidence angle. This improved understanding of the incidence angle behaviour of backscatter increases our ability to interpret and make optimal use of the ASCAT data record and VOD products for vegetation monitoring.

3.1.4 RADAR SATELLITE IMAGERY FOR DETECTING BARK BEETLE OUTBREAKS IN FORESTS[3]

The overall objective of this paper is to review the state of knowledge on the application of radar data for detecting bark beetle attacks in forests. Due to the increased availability of high spatial and temporal resolution radar data (e.g. Sentinel-1 (S1)), the question is how this time series data can support operational forest management with respect to forest insect damage prevention. Furthermore, available radar systems will be listed and their potential for detecting bark beetle attacks will be discussed. To increase the understanding of the potential of radar time series for detecting bark beetle outbreaks, a theoretical background about the interaction of the radar signals with the forest canopy is given. Finally, gaps in the available knowledge are identified and future research questions are formulated which could advance our understanding of using radar data for detecting forest bark beetle attacks. Recent Findings. Few studies already demonstrate the high potential of S1 time series data for forest disturbance mapping in general. It was demonstrated that multi-temporal S1 data provide an excellent data source of describing the phenological characteristics of forests, which provide the basic knowledge for detecting bark beetle induced forest damages. It has been found that the optimal time for data acquisition is April to June for the pre-event and August to October for the post-event acquisitions. For detecting bark beetle induced forest damages, the literature review shows that mono-temporal radar data are of limited use, that shorter wavelength (e.g. C-band; X-band) have a higher potential than longer wavelength such as L-band and that the current S1 time series data have a high potential for operational applications.

3.1.5 COMPARISON OF LONG SHORT-TERM MEMORY NETWORKS AND RANDOM FOREST FOR SENTINEL-1 TIME SERIES BASED LARGE SCALE CROP CLASSIFICATION[4]

To ensure future food security, improved agricultural management approaches are required. For many of those applications, precise knowledge of the distribution of crop types is essential. Various machine and deep learning models have been used for automated crop classification using microwave remote sensing time series. However, the application of these approaches on a large spatial and temporal scale is barely investigated. In this study, the performance of two frequently used algorithms, Long Short-Term Memory (LSTM) networks and Random Forest (RF), for crop classification based on Sentinel-1 time series and meteorological data on a large spatial and temporal scale is assessed. For data from Austria, the Netherlands, and France and the years 2015–2019, scenarios with different spatial and temporal scales were defined. To quantify the complexity of these scenarios, the Fisher Discriminant measurement F1 (FDR1) was used. The results demonstrate that both classifiers achieve similar results for simple classification tasks with low FDR1

[3] https://link.springer.com/article/10.1007/s40725-019-00098-z

[4] https://www.mdpi.com/2072-4292/13/24/5000

values. With increasing FDR1 values, however, LSTM networks outperform RF. This suggests that the ability of LSTM networks to learn long-term dependencies and identify the relation between radar time series and meteorological data becomes increasingly important for more complex applications. Thus, the study underlines the importance of deep learning models, including LSTM networks, for large-scale applications.

3.1.6 DOES ASCAT OBSERVE THE SPRING REACTIVATION IN TEMPERATE DECIDUOUS BROADLEAF FORESTS?[5]

Scatterometer observations over land are sensitive to the water content in soil and vegetation, but have been rarely used to study seasonal changes in the plant water status and seasonal development of deciduous trees. Here we use Advanced Scatterometer (ASCAT) observations to investigate the sensitivity of C-band backscatter to spring phenology of temperate deciduous broadleaf forests in Austria. ASCAT's multi-angle looking capability enables the observation of backscatter over a large range of incidence angles. The vegetation status affects the slope of the backscatter-incidence angle relationship. We discovered a maximum in the slope around the month April, hereafter referred to as spring peak, predominantly in regions covered by deciduous broadleaf forest. We hypothesized that the spring peak indicates the average timing of leaf emergence in the deciduous trees in the sensor footprint. The hypothesis was tested by comparing the timing of the spring peak to leaf unfolding observations from the PEP725 phenology database, to the increase of leaf area index (LAI) during spring, and to temperature. Our results demonstrate a good agreement between the ASCAT spring peaks, phenology observations and temperature conditions. The steepest increase in LAI however lags behind the ASCAT peak by several days to a few weeks, suggesting that the spring peak in fact marks the timing of maximum woody water content, which occurs right before leaf emergence. Based on these observations, we conclude that the ASCAT signal has a high sensitivity to spring reactivation and in particular water uptake of bare deciduous broadleaf trees. Our findings might provide the basis for novel developments to estimate eco-physiological changes of forests during spring at large scales.

3.1.7 ANALYSIS OF SHORT-TERM SOIL MOISTURE EFFECTS ON THE ASCAT BACKSCATTER-INCIDENCE ANGLE DEPENDENCE[6]

The incidence angle dependence of C-band backscatter is strongly affected by the presence of vegetation in the sensor footprint. Many studies have shown the suitability of this dependence for studying and monitoring vegetation dynamics. However, short- term dynamics in the backscatter-incidence angle dependence remain unexplained and indicate that secondary effects might be superimposed on the vegetation component.

In this study, we hypothesize that the observed short-term dynamics are caused by soil moisture. We investigate the effect by exploring relationships between the slope of the backscatter-incidence angle dependence (σ') from the Advanced Scatterometer (ASCAT) and soil moisture, rainfall, temperature, and leaf area index. We carry out the analysis over six study regions in Portugal, Austria, and Russia with different climate, land cover, and vegetation cycles.

Our results indicate that soil moisture has an effect on σ'. Spearman correlations of σ' anomalies with soil moisture anomalies are stronger than with any other variable in most study regions and range from -0.38 to -0.70. Even when accounting for effects of water on canopy, correlations between σ' and soil moisture remain relatively strong, ranging from -0.14 to -0.46. These results confirm the presence of secondary effects in the dynamic σ', which need to be corrected for when applying σ' in studies of vegetation dynamics. A correction

[5] https://www.sciencedirect.com/science/article/pii/S0034425720304120

[6] submitted

may be achieved by the application of a suitable smoothing on σ' (i.e., removing high frequency signal components), by masking observations taken under wet conditions, or by the use of models that explicitly account for the effect of soil moisture on σ'.

4 IMPACT OF WORK

The ESA Living Planet Fellowship has allowed me to increase my collaboration within remote sensing of vegetation, give presentations at conferences and invited talks, and has increased my involvement in international projects. It has also motivated me to write a proposal for the Austrian Science Fund. In addition, the Fellowship was one of the main motivations of TU Wien to offer me a permanent Senior Scientist position. Without the ESA Living Planet Fellowship I would not be at the place in my career where I am now.

4.1 COLLABORATIONS

Collaboration with Susan Steele Dunne has intensified during my one month stay at TU Delft. As a result we work together on numerous papers. In addition, I was part of the exam committee of her Master's student Ashwini Petchiappan. Furthermore, I am co-author on several papers of Susan Steelde-Dunne, and TU Delft PhD student Saeed Khabbazzan. Due to long-term illness and the pandemic, the second and third research visits to TU Delft, and visits to Vandersat and Diego Miralles at Ghent University did not take place.

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4.2 INVITED TALKS, CONFERENCE CONVENER AND GUEST EDITORSHIPS

The ESA Living Planet Fellowship supported me in developing my research in vegetation monitoring using microwave observations. A direct result of this was convening two sessions at EGU:

- Global Earth observation and in-situ data for improved understanding of terrestrial ecosystem dynamics
- Remote sensing of interactions between vegetation and hydrology.

This also led to a guest editorship in Biogesciences and HESS on **Microwave remote sensing for improved understanding of vegetation–water interactions**. My work on vegetation monitoring using Sentinel-1 and as ESA Living Planet Fellow led to several invited talks and participation in the ESA Terrestrial Carbon Science Cluster.

- **Sentinel-1 for High Resolution monitoring of vegetation dynamics**, ESA Terrestrial Carbon Science Cluster 1st Coordination Meeting June 23rd 2021, online.
- **Soil moisture and Vegetation monitoring with microwave remote sensing.** Lecture PhD course University of Oulu, October 12th 2021, online.
- **Metop ASCAT and Sentinel-1 for vegetation monitoring.** WMO/EUMETSAT Workshop Satellite products for drought monitoring and agro-meteorological applications. 22-25 October 2018, EUMETSAT HQ, Darmstadt, Germany.

4.3 RELATED PROJECTS

The expertise gained in the Fellowship led to my participation in the ESA Land Carbon Constellation project, where I am working on model operators to include Metop ASCAT observation in the Dalec/Bethy model. Furthermore, I am included in the Austrian Science Fund Cluster of Excellence Transition4Climate project as a key researcher for my expertise on vegetation monitoring with radar observations. The pre-proposal has been submitted to the Austrian Science Fund.

The last year I have written a proposal for a four-year Senior PostDoc project from the Austrian Science Fund. This has been submitted on December 10th 2021. When obtaining this project, this would allow me to work on Sentinel-1 to monitor vegetation phenology across scales. Furthermore, part of this project is to obtain my Habilitation, which allows me to supervise PhD students in Austria.

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