Does NDVI explain spatial and temporal variability in sap velocity in temperate forest ecosystems?

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Abstract. Understanding the link between vegetation characteristics and tree transpiration is a critical need to facilitate satellite-based transpiration estimation. Many studies use the normalized difference vegetation index (NDVI), a proxy for tree biophysical characteristics, to estimate evapotranspiration. In this study, we investigated the link between sap velocity and 30 m resolution Landsat derived NDVI for twenty days during two contrasting precipitation years in a temperate deciduous forest catchment. Sap velocity was measured in the Attert catchment in Luxembourg in 25 plots of 20 × 20 m covering three geologies with sensors installed in 2-4 trees per plot. The results show that, spatially, sap velocity and NDVI were significantly positively correlated in April, i.e., NDVI successfully captured the pattern of sap velocity during the phase of green-up. After green-up, a significant negative correlation was found during half of the studied days. During a dry period, sap velocity was uncorrelated to NDVI, but influenced by geology and aspect. In summary, in our study area, the correlation between sap velocity and NDVI was not constant, but varied with phenology and water availability. The same behaviour was found for the Enhanced Vegetation Index (EVI). This suggests that methods using NDVI or EVI to predict small-scale variability in (evapo)transpiration should be carefully applied, and that NDVI and EVI cannot be used to scale sap velocity to stand level transpiration in temperate forest ecosystems.

1 Introduction

Evapotranspiration (ET) is estimated globally as 60% of the total precipitation (Oki and Kanae, 2006) and 80% of total surface net radiation (Wild et al., 2013). This makes ET the second largest component of the water and energy balance. Changes in ET due to climate or land use change, have a major influence on the catchment water balance. Deforestation for example reduces ET (de Oliveira et al., 2018), leading to lower precipitation (Bagley et al., 2014) and higher streamflow (Dos Santos et al., 2018). Teuling et al. (2009) showed that changes in incoming radiation and water availability impact regional ET and runoff. In order to predict these changes, a comprehensive understanding of 'what controls ET' is an important look forward.

The transpiration component of ET, i.e. water loss through stomata, is the largest contributor to total terrestrial ET, (Wang et al., 2014; Wei et al., 2017) and therefore transpiration plays a major role for the global hydrological and biogeochemical cycle. Transpiration is controlled by complex interactions between climate (Awada et al., 2013; e.g. Hasler and Avissar, 2007), soil moisture content (Mitchell et al., 2012), topographic variables such as slope position and aspect (Mitchell et al., 2012), and vegetation characteristics (Williams et al., 2012). With respect to the vegetation biophysical characteristics, it has been shown that tree transpiration differs with leaf area index (LAI) (Wang et al., 2014; Granier et al., 2000), tree height (Ford et al., 2011; Waring and Landsberg, 2011), tree diameter (Jung et al., 2011; Chiu et al., 2016), tree age, (Baret et al., 2018) and phenological stage (Sobrado, 1994). With the advancements of remote sensing and free data availability, there have been many efforts to link (E)T to satellite derived vegetation indices (Carter and Liang, 2018). For example, studying large watersheds, Nagler et al. (2005) found a positive correlation between the Enhanced Vegetation Index (EVI) and Normalized Difference Vegetation Index (NDVI) and ET in a riparian area, and Szilagyi (2000) found a positive correlation between NDVI and ET in a mixed forest. Using the NDVI as a measure for vegetation biophysical properties has two major drawbacks: the saturation of NDVI at high biomass and the sensitivity to soil reflectance (Huete, 1988). Despite these drawbacks, NDVI is the most commonly used index for vegetation monitoring (Glenn et al., 2010). The link between NDVI and transpiration or evapotranspiration (E(T)) is used in different ways to either estimate (E)T or to scale *in situ* water flux measurements to the landscape level. Five different ways are described below. First, the NDVI is used to calculate the fractional vegetation cover to estimate (E)T in forests or mixed land use types (Boegh et al., 2009; Maselli et al., 2014; Zhang et al., 2009; Chiesi et al., 2013). Second, NDVI is used to derive a spatio-temporal crop coefficient (the Kc-NDVI method) for grassland and agricultural fields (e.g. Mutiibwa and Irmak, 2013; Kamble et al., 2013; Reyes-González et al., 2018) or natural or mixed ecosystems (Maselli et al., 2014; Hunink et al., 2017). The Kc-NDVI method neglects the soil moisture driven controls on E(T), and this is one of the main drawbacks of using this method in natural vegetation (Glenn et al., 2010). An additional water stress term can be used with the Kc-NDVI equation to model dry ecosystem ET or water stressed conditions (Maselli et al., 2014; Park et al., 2017). Third, surface energy balance models use NDVI to parameterise aerodynamic roughness length and displacement height (Su, 2002), and models based on the Penman-Monteith equation use NDVI to parameterise surface conductance (Zhang et al., 2009). Fourth, the surface temperature-NDVI (Ts-VI) 'triangle' method is used to derive soil moisture stress scalar to constrain ET. If pixels from different surface conditions are plotted in a Ts-NDVI scatterplot, they form a triangle pattern. The evaporative fraction and the Priestley-Taylor coefficient – the ratio potential evaporation over equilibrium evaporation – can be parameterised from that triangle, which are consequently used to calculate ET (Zhu et al., 2017; Jiang and Islam, 2001; Mallick et al., 2009). Fifth, NDVI is used, e.g. as a proxy for stomatal conductance or absorbed photosynthetically active radiation, to scale *in situ* measured ET to larger regions (Kim et al., 2006; Rahman et al., 2001). Thus, in many different approaches, NDVI plays a key role in estimating transpiration.

The above mentioned studies often derive the NDVI from MODIS or AVHRR data which have a spatial resolution of 250 m and 1 km (except for Reyes-González et al. (2018); Kim et al. (2006); Rahman et al. (2001); Su (2002), who used airborne data or high resolution satellite data (Landsat or IKONOS)). The NDVI is often compared with ET derived from different flux towers with a footprint length of 100 to 1000 m (Kim et al., 2006), or a water balance model. Therefore, these studies encompass large spatial areas, with a larger variation in vegetation cover and sometimes multiple land use types. Despite that the availability of high spatial resolution satellite products increases rapidly (e.g. Sentinel series), there is a lack of studies that investigate the link between satellite derived NDVI and the water balance on the scale of forest patches or smaller. At the same time, there is a trend towards hyper-resolution land surface modelling and monitoring (Bierkens et al., 2015), where for example 30 m Landsat derived NDVI data is used as a proxy for land cover in a continental land surface model (Chaney et al., 2016). For many processes or parameters it is, however, unknown if they can be applied at such high resolutions. Therefore, in this study we aim to understand if the relation between NDVI and transpiration is also valid on the scale of forest patches by using 30 m resolution NDVI data.

Investigating the link between transpiration and NDVI requires high-resolution satellite data as well as a dense network of in-situ transpiration observations. In the Attert catchment, a dense network of sensor clusters with – among others – sap velocity sensors allows for a detailed study of the link between tree transpiration and NDVI. For this catchment Hassler et al. (2018) showed that variability in sap velocity is mainly controlled by tree characteristics, such as tree diameter and tree height and site characteristics, such as geology and aspect. The aim of our study is to investigate the link between transpiration and NDVI using measurements of sap velocity combined with 30 m resolution NDVI data. Hassler et al. (2018) showed that small-scale variability in sap velocity was related to tree structural characteristics, and therefore we expect sap velocity and NDVI to be correlated. We hypothesise this correlation to be positive, because we expect that forest stands with a higher leaf biomass (higher NDVI) will have a larger sap velocity.

Under water stressed conditions, stomatal closure reduces tree transpiration to limit the risks of hydraulic failure. Among others, leaf area and leaf shedding play a role in mitigating these risks. To study the effect of water stress on the link between transpiration and NDVI, two growing seasons with above and below average precipitation are compared.

2 Material and methods

2.1 Site description

The study was carried out in the Attert catchment in Midwestern Luxembourg. This area was chosen because of its small-scale diversity in geology and soil hydrological conditions. The 288 km^2 sized catchment lies on the border of the Ardennes Massif and the Paris Basin. The three distinct geologies in the catchment are schists, sandstone and marls (Figure 1). Soils vary between sand and silty clay loam (Müller et al., 2014). The land use is characterised by coniferous and deciduous forest on the hillslopes in the sandstone area, and grassland or agriculture in the valleys in the marl area and on the plateaus in the schist area. The elevation of the studied clusters ranges from 217 to 473 m above sea level. The average monthly temperature ranges from 0 °C (January) to 18 °C (July), the average yearly precipitation is 850 mm, and the mean annual evapotranspiration is 570 mm (Müller et al., 2014).

Within the CAOS research unit, a monitoring network was set up in the Attert catchment including 29 sensor clusters in forest (of which 25 are used in this study) in order to provide a new framework for hydrological models for catchments at the lower meso-scale (Zehe et al., 2014). A cluster site covers 20 × 20 m, and in each sensor cluster, soil moisture content (θ), meteorological characteristics, and sap velocity were measured. More information about these measurements can be found in Renner et al. (2016) and Hassler et al. (2018).

Soil moisture content was measured in three soil profiles in each cluster site using Decagon 5TE sensors at three depths (10, 30 and 50 cm). For this study, the average θ at 30 cm depth was calculated for the catchment. Wind speed and relative humidity (RH) were measured above grass at a weather station from the CAOS research unit (Figure 1). Mean daily air temperature (T_a) was available from the Roodt weather station, and global radiation

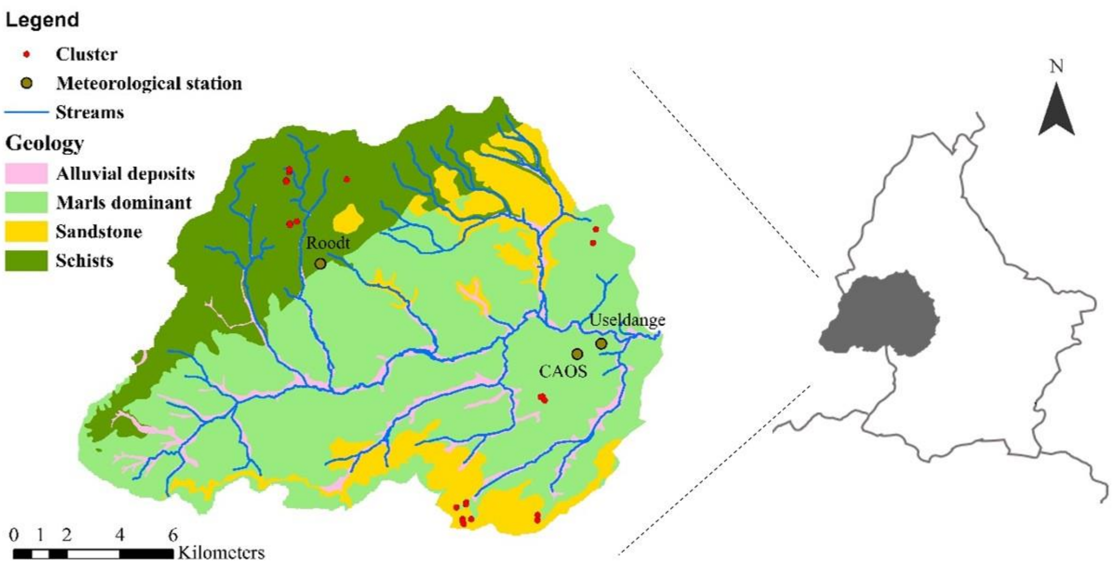

Figure 1: The geology of the Attert catchment and its position in Luxembourg. Sandstone in the catchment is a combination of Buntsandstein sandstone in the north and Lower Jurassic sandstone in the south. Also shown are the main streams, measurement clusters, and meteorological stations.

(R_g) was available from the Useldange weather station. Daily potential evaporation (E_p) was calculated for the catchment using the FAO Penman-Monteith equation (Allen et al., 1998). Table 1 lists the used symbols and their unit.

2.2 Meteorological conditions

In this study, two meteorologically contrasting years were analysed: 2014, a growing season with above average precipitation and 2015, a growing season with below average precipitation. For the months May and June,meteorological conditions were not significantly different between 2014 and 2015, but for July and August, mean daily temperature, vapour pressure deficit (D), global radiation, and potential evaporation were higher in 2015. E_p was 46% (July) and 107% (August) higher in 2015 compared to the same months in 2014 (Figure 2). Total precipitation from April to August was 489 mm in 2014 and 249 mm in 2015, compared to an average of 374 mm for the years 2011 to 2017. September 2015 was wet with a total precipitation of 160 mm. The high E_p and below average precipitation in 2015 resulted in a cumulative precipitation deficit of 113 mm at the end of August (Figure 3). Consequently, θ was low in the summer of 2015 (Figure 2).

2.3 Data

2.3.1 Sap velocity

Sap velocity is used as a measure of tree transpiration (e.g. Smith and Allen, 1996). In summary, in this method, heat is applied to the water in the xylem of the tree trunk, and this heat is carried upwards with the water. Temperature sensors monitor the time it takes before the heat pulse

Table 1: Meteorological characteristics and their unit.

Variable	**Symbol**	**Unit**
Evapotranspiration	ET	mm d^{-1}
Potential evaporation	E_p	mm d^{-1}
Vapour pressure deficit	D	kPa
Daily total global radiation	R_g	W m^{-2}
Soil moisture content	θ	m^3 m^{-3}
Daily average temperature	T_a	ºC

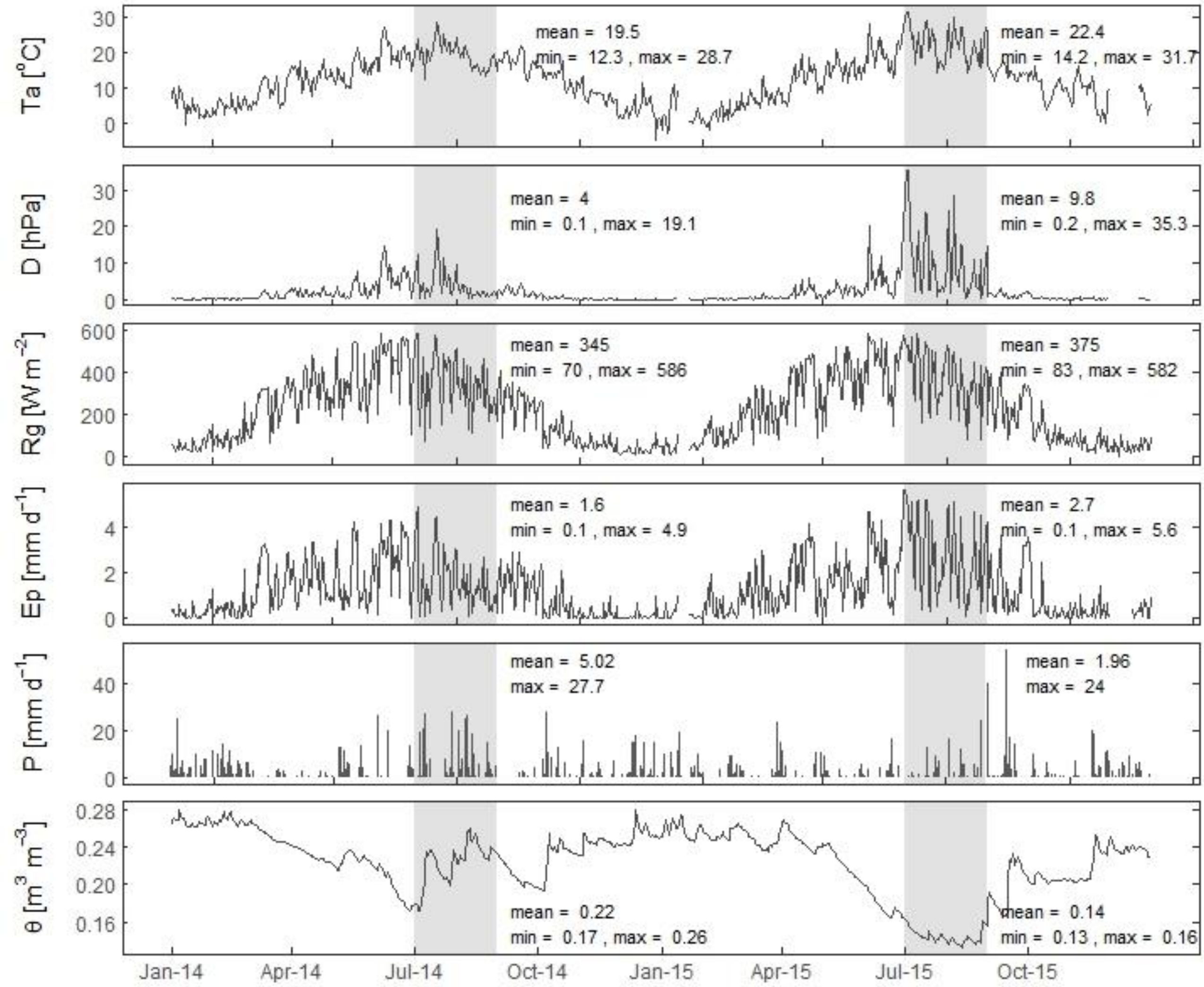

Figure 2: Meteorological conditions in 2014 and 2015. Daily average temperature (T_a), vapour pressure deficit (D), global radiation (R_g), potential evaporation (E_p), precipitation (P), and soil moisture content (θ). The min, mean, and max values are calculated for July and August in both years, indicated by the grey box.

reaches the sensor. This time is related to the velocity of the water in the xylem. More information about sap velocity measurements can be found in e.g. Smith and Allen (1996).

At each sensor cluster (all located in deciduous forest stands), four trees roughly representative for the cluster site, were selected for the sap velocity measurements. The main deciduous tree species in the area are beech (*Fagus sylvatica* L.) and oak (*Quercus robur* L. and *Quercus petraea* (Matt.) Liebl.), less abundant are hornbeam (*Carpinus betulus* L.), maple (*Acer pseudoplatanus* L.), and alder (*Alnus glutinosa* (L.) Gaertn.). Table 2 shows the presence of the different species in this study. Sap velocity was measured at the north facing side of the stems using sap flow sensors manufactured by East 30 Sensors in Washington, US. From the measured temperatures, sap velocities were calculated based on the equation of Campbell et al. (1991), which is recommended by the manufacturer. Afterwards, a wounding correction was performed following Burgess et al. (2001). Sap velocity differs with horizontal depth in a tree, and this radial variability is one of the main sources of uncertainty in sap velocity measurements (Hernandez-Santana et al., 2015). To account for the radial velocity profile, the sensors measure at three depths: 5, 18 and 30 mm. Following Hassler et al. (2018), for each tree, the sensor with the highest mean daily sap velocity was selected. Trees with less than 80% available data from June to August, or with a prolonged period of negative sap velocity were excluded from the analysis. This resulted in a data set with

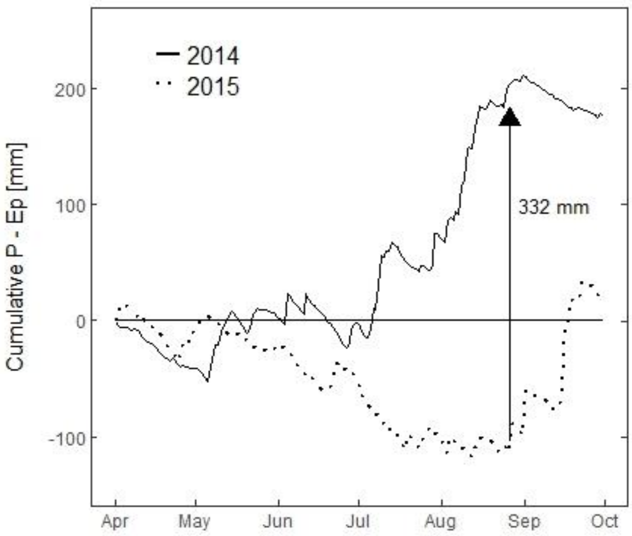

Figure 3: Cumulative precipitation surplus (P – E_p) from April to October for 2014 and 2015. The difference in precipitation surplus between the two years was largest at the end of August, as indicated by the arrow.

73 trees at 25 sensor clusters (Table 2). For each cluster, the mean daily sap velocity (from 8 am to 8 pm local time) was calculated. To match the spatial scale of the sap velocity data to the NDVI data with a 30 m resolution, mean daily sap velocity was calculated for each cluster.

Sap velocity measurements can be scaled up to whole tree transpiration from the total sapwood area for each tree (Smith and Allen, 1996), but these data were not available within our study area. Alternatively, a species and site specific allometric equation between tree diameter at breast height and sapwood area can be used to calculate tree total sap flow, but this conversion introduces uncertainties (Gebauer et al., 2012; Ford et al., 2004). Therefore, we used sap velocity directly in our study.

2.3.2 NDVI and EVI

The vegetation indices were calculated from Landsat-7 (ETM+ sensor) and Landsat-8 (OLI sensor) surface reflectance data obtained from EarthExplorer of the U.S. Geological Survey. Both sensors acquire images with a spatial resolution of 30 m and combined, they have a temporal resolution of 8 days. The overpass time of the satellites is 10:27 AM. Clouds and cloud shadows were removed from the images using the cloud quality information delivered with the data product, and this automatic procedure was followed by a visual check to remove cloudy pixels. After the cloud removal, surface reflectance values were extracted for each cluster centre using bilinear interpolation, where the four closest raster cells are interpolated. Images were removed when surface reflectance information was available for less than five clusters or for only one geology type. This resulted in a total availability of 20 Landsat images, 11 for the growing season of 2014 and 9 for the growing season of 2015. NDVI and EVI were calculated as:

$$NDVI = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{Red}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{Red}}}$$

$$EVI = \frac{(\rho_{\mathrm{NIR}} - \rho_{\mathrm{Red}})}{\rho_{\mathrm{NIR}} + 6 * \ \rho_{\mathrm{Red}} - 7.5 * \ \rho_{\mathrm{Blue}} + 1} * 2.5$$

Where ρ is the surface reflectance in the near infrared (NIR), red, and blue part of the electromagnetic spectrum.

Table 2: Cluster site characteristics.

Geology	# clusters	# studied trees	# beech/ oak/ other	Elevation (min - max)	# stems per cluster (min - max)	mean cluster DBH (min - max)
Sandstone	9	29	21/7/1	217-284	9-54	2-44
Marl	5	13	2/8/3	283-351	16-34	5-17
Schist	11	31	23/5/3	428-473	20-346	4-37

2.3.3 Tree and cluster site characteristics

To study the effect of static vegetation- and environmental characteristics on sap velocity and NDVI, correlations with tree- and environmental characteristics were calculated. Information on semi-static tree and cluster site characteristics were available from Hassler et al. (2018). For every cluster, the total number of stems was counted, and the DBH was measured for each tree with a circumference of more than 4 cm (Table 2). The tree height was estimated for every tree where sap velocity was measured, and for each cluster site, aspect was noted. Elevation and geology are derived from a digital elevation model and a geological map.

3 Results

3.1 Temporal and spatial variability in sap velocity and NDVI

The seasonality in sap velocity is clearly visible, with a steep increase in April and a decrease in October (Figure 4). Mean daily sap velocity for July and August was highest for beech trees in the sandstone area (8.9 cm h^{-1} in

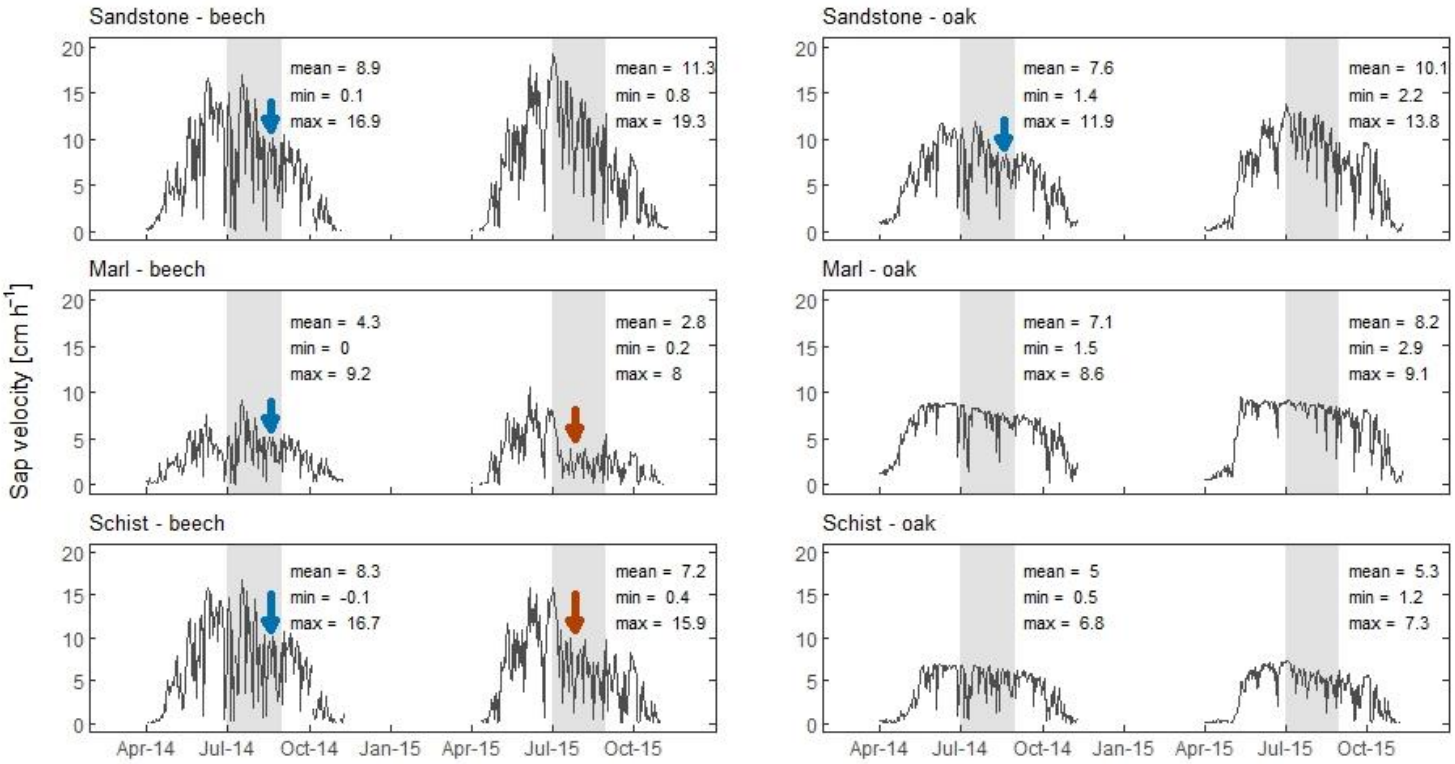

Figure 4: Mean daily sap velocity for beech and oak trees in the three different geologies. The drop in sap velocity in August 2014 (blue arrow) is related to a lower incoming radiation, while the drop in August 2015 (red arrow) is not related to a lower incoming radiation, but falls into a period of below average precipitation and low soil moisture content. The min, mean, and max values are calculated for July and August in both years, indicated by the grey box.

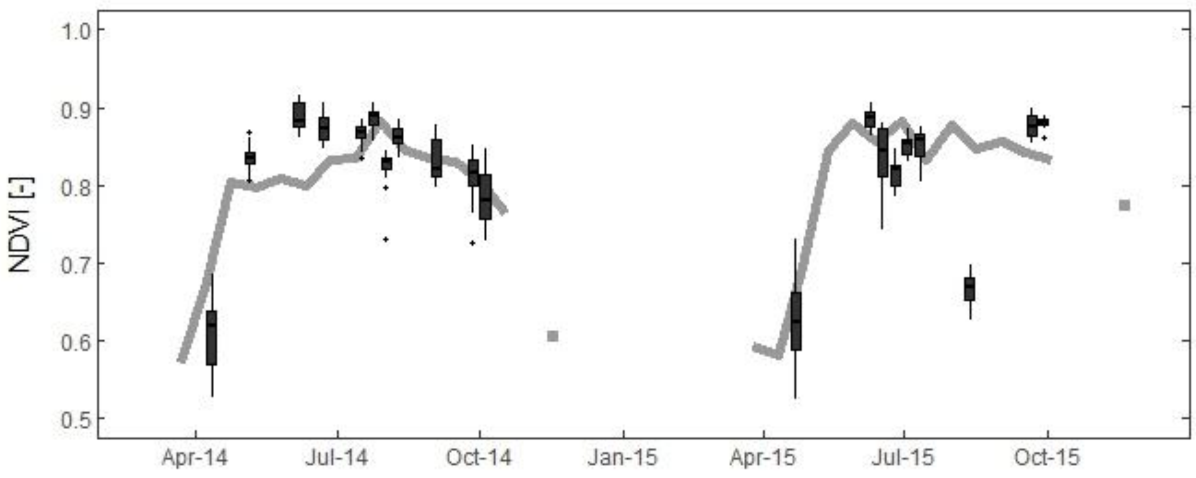

Figure 5: Observed NDVI dynamics during the growing seasons of 2014 and 2015. The grey line and dots represent the mean NDVI over the forested clusters derived from the MOD13Q1 product of MODIS. It provides a better overview of the seasonal course. The twenty boxplots (in black) show the variability in Landat derived NDVI over the studied clusters for each studied day.

2014 and 11.3 cm h^{-1} in 2015) and lowest for beech trees in the marl area (4.3 cm h^{-1} in 2014 and 2.8 cm h^{-1} in 2015). In July 2014, sap velocity was low for part of the trees, which corresponds to a low R_g. Also from July to August 2015, the period with little rainfall, sap velocity was low for part of the trees located in the marl and schist area. The reduced sap velocity in 2015 did not correlate with a low R_g. Redundancy analysis showed that in 2014, 78% of the variability in daily sap velocity was explained by R_g and T_a. In 2015, R_g, T_a, and θ together explained 65% of the variability in sap daily velocity.

The phenological cycle is clearly visible in the temporal dynamics of NDVI with a rapid green-up in April (Figure 5). In April, the mean Landsat derived NDVI over the clusters was 0.62 (± 0.05), as compared to 0.82 (± 0.05) during the fully developed stage of the vegetation. On August 12, 2015, the NDVI of all clusters was low, which did not appear in the MODIS NDVI product. These pixels were not removed by the cloud removal procedure, but haze is visible in the image, which possibly influenced the cluster pixels. Unfortunately no other cloudless images were available for the second half of July and August in 2015, the driest months of the summer.

3.2 Correlation between sap velocity and NDVI

Analysing all clusters together for all 20 days, a moderate positive correlation was found between sap velocity and NDVI ($p < 0.001$, Pearson's $r = 0.47$) (Figure 6a). Considering temporal correlation, both sap velocity and NDVI had low values at the start and end of the growing season and high values in summer. This makes that sap velocity and NDVI were positively correlated for 22 of the 25 clusters ($p < 0.05$) (Figure 6b-e). Considering the months May to September only, when the canopy was in full leaf, there was no (significant) correlation between sap velocity and NDVI for 22 of the 25 clusters.

Scatterplots of spatial variability in sap velocity and NDVI show three different patterns: 1) a significant linear positive correlation (Figure 7a, d: Pearson's r between 0.50 and 0.60), 2) a significant linear steep negative correlation (Figure 7b, e: Pearson's r is between – 0.51 and – 0.70), and 3) no significant correlation (Figure 7c, f). The positive correlation coefficient between sap velocity and NDVI was found in April in both years. This was the beginning of the growing season, and sap velocity and NDVI values were below average. For five of the

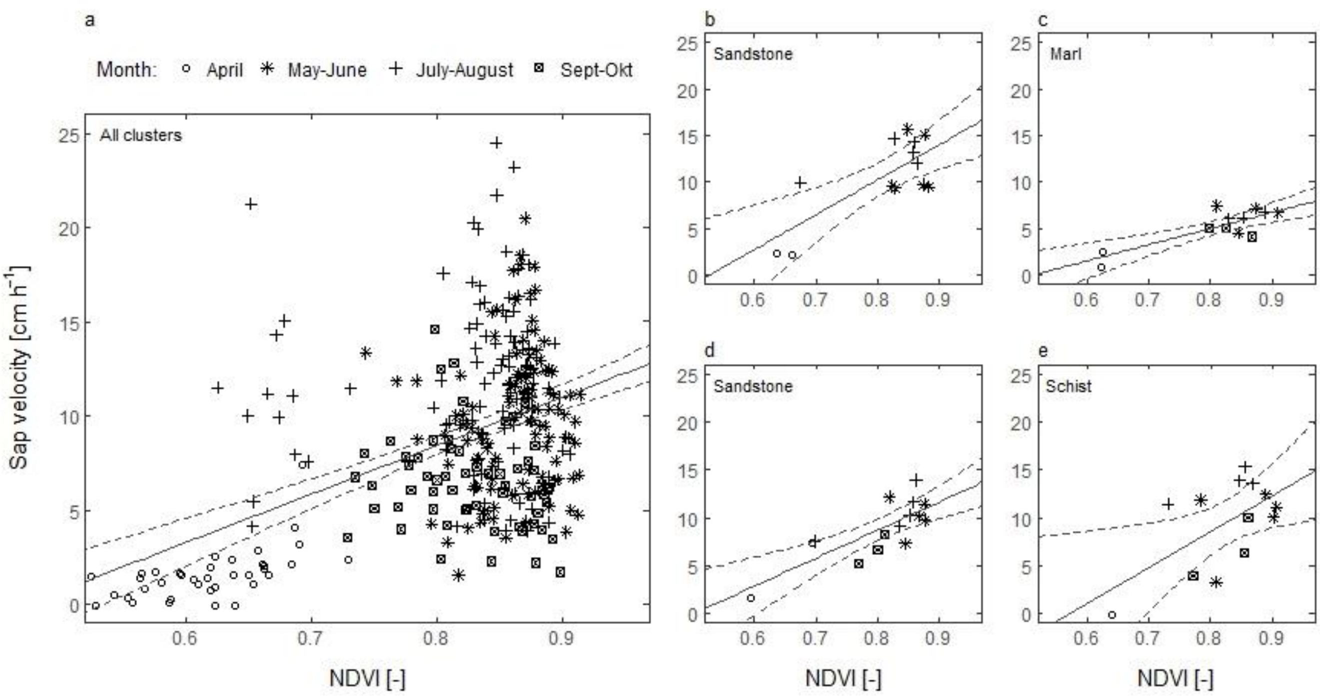

Figure 6: Temporal correlation between sap velocity and NDVI for all twenty studied days in 2014 and 2015. a) For all clusters together, sap velocity and NDVI were positively correlated ($p < 0.001$, $R^2_{adj} = 0.22$). b-e) the correlation for four different clusters in different geologies. For each shown cluster, the correlation is significant ($p < 0.05$). For one of the 25 clusters, the correlation is not significant and for two clusters the correlation is significant only at $p < 0.1$. The dashed line represents the 95% confidence interval.

studied days during the growing season of 2014 and early-June and September 2015, sap velocity and NDVI were negatively correlated. For five days in 2014 and six days in 2015, sap velocity and NDVI were uncorrelated.

3.3 Correlation between sap velocity and NDVI in relation to soil moisture content (θ)

Figure 8a shows the dynamic changes in the correlation coefficient between sap velocity and NDVI. In both years, the correlation coefficient was positive at the beginning of the growing season (April) and negative or close to zero during the rest of the year. In the year 2014, no trend was visible in the variability of the correlation coefficient. In 2015, the correlation coefficient was initially positive and became negative in May. As the growing season progressed and θ dropped (to a minimum of $\theta = 0.13$ $m^3\,m^{-3}$ in mid-August), the correlation got weaker and insignificant. At the end of September, when θ increased following high precipitation, the correlation between sap velocity and NDVI was again negative. Studying all days together, sap velocity and NDVI were positively correlated during the period of highest θ (in April, $\theta > 0.22$ $m^3\,m^{-3}$) (Figure 8b). Contrastingly, at high θ during September 2015 ($\theta > 0.20$ $m^3\,m^{-3}$), sap velocity and NDVI were negatively correlated. The correlation coefficient was close to zero when θ was lowest. At intermediate θ, the correlation coefficient was mostly negative.

3.4 Effect of static vegetation and environmental characteristics on sap velocity and NDVI

The effects of static vegetation and environmental characteristics on sap velocity and NDVI were calculated. This was also done to check if dependency on one of these characteristics could explain the negative correlation between sap velocity and NDVI. Assessing individual trees, sap velocity was related to tree DBH and tree height, but on cluster level, sap velocity was not or moderately dependent on these characteristics (Table 3). The number of stems and mean tree DBH per cluster did not correlate with sap velocity. For some days, sap velocity was

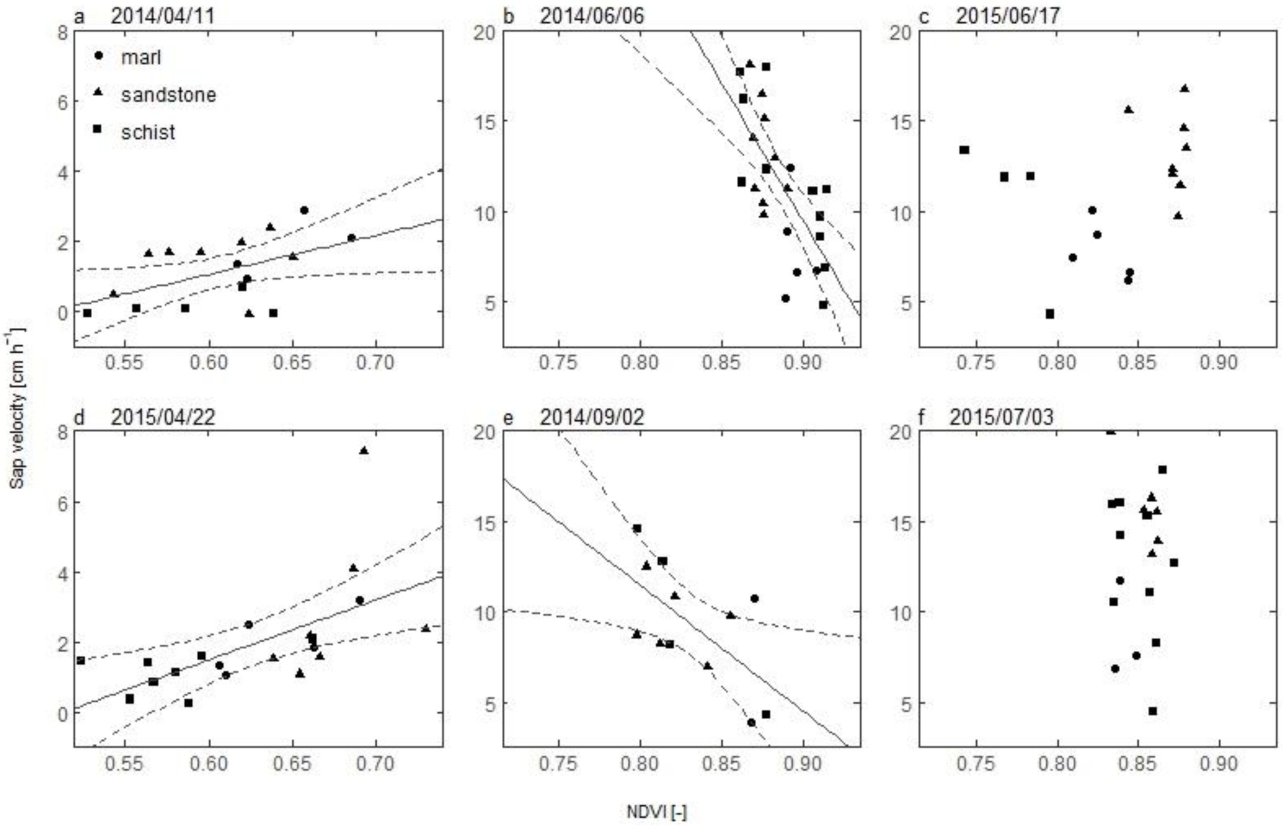

Figure 7: Relationship between sap velocity and NDVI for six days. Each dot represents one cluster in the sandstone, schist and marl area. The dashed line represents the 95% confidence interval. a + d) April 2014 and 2015, during the period of green-up. At the b) start and e) end of the growing season in 2014. c + f) At the beginning of the dry summer of 2015.

higher in clusters with higher trees. For most studied days, sap velocity for beech trees was higher than for oak trees, but this difference was usually not significant. Altitude and sap velocity were negatively correlated in April for both years. Geology and aspect explained part of the variability in sap velocity, especially during summer 2015, when sandstone clusters had a higher sap velocity than schist and marl clusters, and north facing slopes had a higher sap velocity than south facing slopes. The different cluster characteristics were not independent and therefore, a relation between two variables could also have been the result of a causal relation with another variable.

Cluster averaged tree characteristics were usually not related to NDVI, and their direction of influence was not consistent. Also the change of NDVI with altitude was not consistent over the year, but in April both years, the correlation was negative. In both years, schist clusters had the lowest NDVI in April ($p < 0.1$ in 2014). From June till August 2015, sandstone clusters had the highest NDVI, except for June 9 and June 25. Variability in species and aspect were correlated with variability in NDVI only for a few days.

4 Discussion

4.1 Sap velocity and scaling to tree transpiration

In the present study, mean sap velocity was calculated for the 2 – 4 trees in each cluster. This is only a small selection of the total number of trees per cluster, which varied from 9 to 346, with a median of 34 trees per cluster. The trees selected for sap velocity measurements are roughly representative for the cluster with respect to species

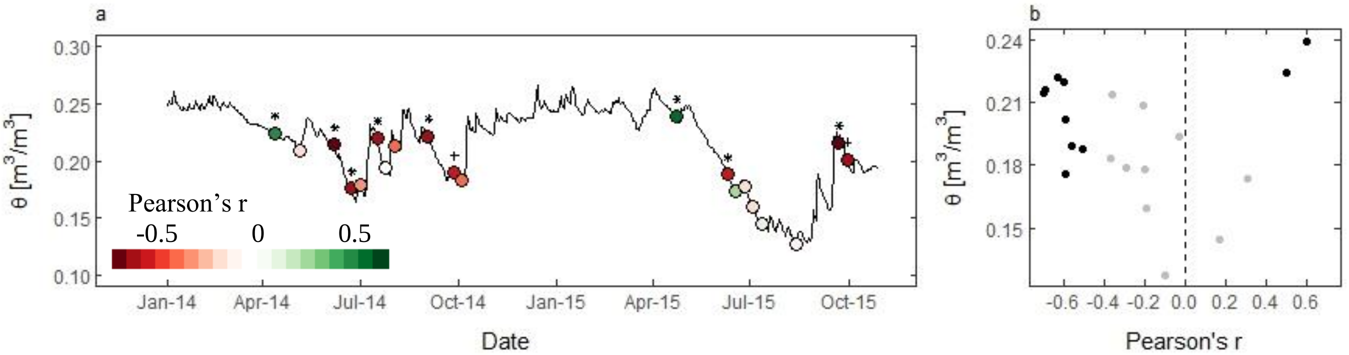

Figure 8: Relationship between sap velocity and NDVI and observed soil moisture content. a) The average soil moisture content at 30 cm depth over the clusters. The colours indicate the spatial correlation coefficient (Pearson's r) between sap velocity and NDVI for the 20 studied days. Symbols indicate if the correlation is significant at $p < 0.05$ (*) or at $p < 0.1$ (+). b) For the 20 studied days the soil moisture content and Pearson's correlation coefficient. Black dots indicate that $p < 0.1$.

and DBH. But velocity of the sap depends on tree DBH, height, species, and tree age (Gebauer et al., 2012; Ryan et al., 2006), and therefore, making a true representative selection remains to be challenging.

We looked for a relationship between tree sap velocity and a canopy trait, NDVI. Please note that two scaling steps are required to scale sap velocity up to the canopy level: a first step to scale from sap velocity to whole tree transpiration and a second step from tree to stand transpiration. In this study, measurements of sap velocity were preferred over whole tree or stand transpiration, because scaling introduces uncertainties, especially when sapwood area is not known (Gebauer et al., 2012; Ford et al., 2004). An empirical scaling formula can be used to calculate whole tree transpiration from 1) sap flow, 2) tree DBH, and 3) a species and site specific parameter. On individual tree level, trees with a larger DBH had a higher sap velocity, which is also known from other studies (Jung et al., 2011). Calculating whole tree transpiration from sap velocity would have thus increased the mutual differences among clusters, but usually would have not changed the order of values and direction of correlation with NDVI. The species specific parameter in the scaling formula would have increased the differences in transpiration between beech and oak trees. This is because beech trees in this study had, on average, a larger sap velocity and, despite the lower DBH, a higher average sapwood area.

4.2 Temporal and spatial variability in sap velocity and NDVI

The moments of vegetation green-up and leaf senescence are reflected in both sap velocity and NDVI as they increase in April and decrease in October. Comparing the summer (July and August) of 2014 and 2015, the higher potential evapotranspiration in 2015 resulted in a higher sap velocity for beech and oak trees in the sandstone area compared to 2014. For the beech trees in the marl and schist area however, mean sap velocity was lower in summer 2015. This drop in sap velocity in 2015 could not be attributed to a reduction in atmospheric demand or available energy (Figure 9), and was likely the result of stomatal closure in response to water stress. No drought related reduction was observed in NDVI, also no lagged effect. This indicates that trees were conservative with water and closed their stomata to prevent transpirational water loss, but that this stomatal closure did not observably affect LAI. NDVI saturates at high LAI (Huete et al., 2002), and therefore effects of mild drought might not be visible in NDVI. But under the transient drought conditions in 2015, an effect on NDVI can also not be expected, as drought related early senescence and other structural vegetation changes become visible only after a prolonged dry period (Eklundh, 1998).

Considering the spatial variability, Hassler et al. (2018) found that in the Attert catchment, tree characteristics (species, DBH and tree height) explained 22% of the variability in sap velocity. Interestingly, our study showed

Table 3: Seven (semi-)static cluster characteristics and whether they are significantly correlated (p < 0.05) with spatial variability in mean sap velocity (α) and NDVI (β). Parenthesis indicate a significance level of p < 0.1. The results are based on Pearson's correlation for numerical data and one-way ANOVA for species, geology, and aspect. The mean cluster DBH is the mean DBH of all trees in the cluster, while the mean tree height is the mean of the sap velocity trees only. Species classes are beech, oak, or a mixture. The number of stems, DBH, and tree height are not independent. Mean tree height, aspect, and altitude are related to geology. The light grey shading indicates that the correlation between sap velocity and NDVI was positive for this day, while a dark grey shading indicates a negative correlation.

Year	Date	Number of stems	Mean tree DBH	Mean tree height	Species	Altitude	Geology	Aspect
2014	11-04			α		α	α (β)	(α)
	05-05	β			(α)			(β)
	06-06					(β)	α (β)	(α)
	22-06	(α) β	β	β		β	β	α
	16-07			α (β)			(α)	(α)
	24-07		β				(α)	(α)
	01-08			(α)		β	α β	α
	09-08			(β)				(α)
	02-09				(α) β		β	(α) β
	26-09						β	
	04-10							β
2015	22-04	(α) β	β	β		α β	(α) β	
	09-06	β	β	β	(α)	β	α β	α
	17-06	(β)		β	(α)	β	α β	α
	25-06			(β)	α		α	α
	03-07				(α)		α	α
	11-07	β		α β		(α) β	α β	α
	12-08			α		α	α	(α) (β)
	21-09			(α)				(β)
	29-09			(α)				(α)

that cluster mean tree characteristics did not explain variability in cluster mean sap velocity during most of the growing season (Table 3). This is likely because of the smaller variability in sap velocity and tree characteristics on the cluster level as compared to individual trees.

Part of the trees showed a water stress induced drop in sap velocity in 2015. The statistical analysis revealed that during this period, geology and aspect significantly explained part of this spatial variability in sap velocity (Table 3). The higher sap velocity on north facing slopes could indicate the effect of a higher water availability compared to south facing slopes. In the sandstone area, trees maintained high sap velocity during the dry period, but sap velocity was reduced in the schist and marl area. Also this effect of geology is likely related to water availability. Pfister et al. (2017) and Wrede et al. (2015) showed that in the Attert catchment, sandstone has a high storage capacity, because of the deep permeable soils, while the storage capacity is low in the marl and schist area. Furthermore, trees in the sandstone area were on average taller and had a larger DBH. These trees might have been able to access water from deeper layers because of a more developed root system.

4.3 Correlation between sap velocity and NDVI

Temporally, sap velocity and NDVI were positively correlated, because both follow a similar seasonal cycle with lower values in April and October than in summer. Considering only the full leaf period (May – September), sap

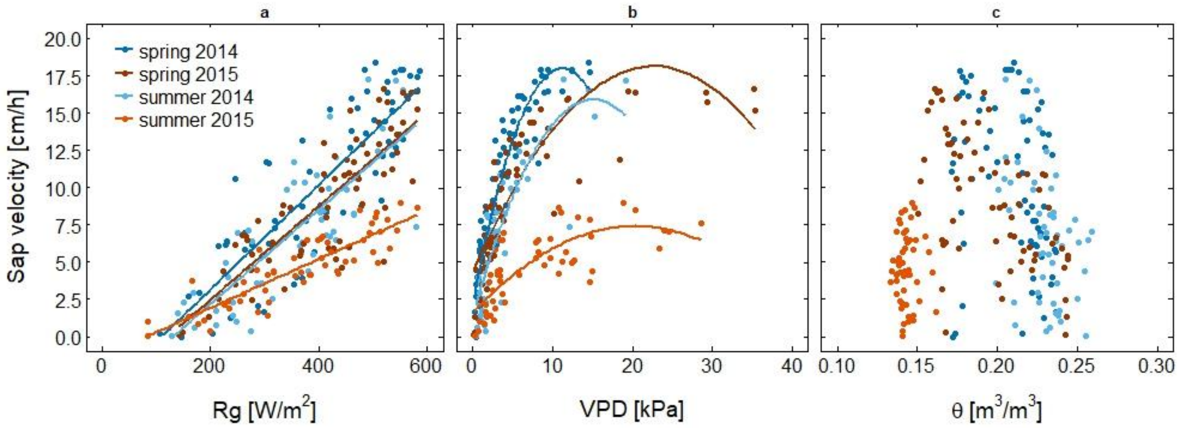

Figure 9: Relationship between sap velocity and meteorological conditions for spring and summer 2014 and 2015 for a beech tree in the schist area. The relationship between mean daily sap velocity and a) global radiation (R_g) b) vapour pressure deficit (D), and c) soil moisture content (θ). In summer 2015, sap velocity is low, despite high R_g and D.

velocity and NDVI were not correlated. Variability in sap velocity during the full leaf period was to a large extent explained by daily variations in R_g and T_a, and these meteorological controls of transpiration are not reflected in the NDVI. Neither is the NDVI affected by daily variations in R_g and T_a.

Considering spatial correlation, three different patterns were found: a positive, negative and no correlation. The different patterns are discussed below. During April in both years, sap velocity and NDVI were positively correlated. This was before complete leaf-out and the spatial variability in NDVI was high. In April, elevation of the clusters significantly explained part of the variability in both sap velocity (Pearson's r = – 0.56 (2014) and – 0.45 (2015)) and NDVI (Pearson's r = – 0.78 (2015)). Onset of greenness varies with elevation and associated temperature differences (Elmore et al., 2012; Kang et al., 2003), and at the moment of image acquisition, the clusters were in different stages of phenological development. This was reflected in both NDVI and sap velocity, and likely explains the positive correlation between them.

The negative correlation between sap velocity and NDVI – a higher sap velocity for lower leaf biomass – was found during most of the studied period, though sometimes weak and not significant. There is no clear explanation for this unexpected result, but four probable reasons are foreseen that could have influenced the correlation. First, for NDVI it is well known that it saturates at high LAI (Huete et al., 2002), which makes the index insensitive to vegetation biophysical and biochemical properties (Gamon et al., 1995). NDVI saturation was found for LAI greater than ~ 4 in a beech forest (Wang et al., 2005) and LAI greater than ~ 5 – 6.5 for a mixed beech, oak and Scots pine forest (Davi et al., 2006). For the clusters in this study, measured LAI in 2012 was on average 4.9 ± 0.4 for the beginning of May (sandstone and marl clusters) and 6.4 ± 0.8 for mid-August (schist clusters) (unpublished data, described in Sun and Schulz (2017)). Therefore the clusters are likely at saturation, which could introduce noise in the data. The negative correlation however seems to be robust even at high values of NDVI. Second, because we studied small-scale variability, the spatial variability in NDVI was low (standard deviation ranges from 0.01 in summer to 0.05 in April). Both could explain the absence of a positive correlation but they do not explain the negative correlation. Third, sap velocity is not per se transpiration (as explained in paragraph 4.1), but a conversion of sap velocity to tree transpiration is not expected to influence the sign of the correlation. Lastly, a correlation with static tree and site characteristics was investigated, but also this was not found to explain the negative correlation.

On half of the studied days, no correlation was found between sap velocity and NDVI, which could be due to noise in the data caused by the saturation of the NDVI signal. Absence of a correlation could also indicate that optical vegetation characteristics are uncoupled from ET; i.e. that no significant control of stomata and vegetation structure on ET was apparent in the Attert catchment. The temporal change in Pearson's r during the growing season of 2015 – a negative correlation during the beginning (begin-June) and end (September) of the growing season, but no correlation during the drier period – hints to an effect of short-term water stress, which is discussed in section 4.4.

4.4 Comparing the dry and wet growing season

Summer 2015 experienced below average precipitation, but was not exceptionally dry. Nevertheless, sap velocity dropped during this dry period. In 2014, when ample soil water was available, temporal variability in sap velocity was strongly coupled with R_g, D, and T_a. During the period of low soil moisture content in 2015 sap velocity was, next to R_g, D, and T_a, also coupled with soil moisture content. The water stress occurred only for a short time period, and therefore no change in NDVI was apparent. Given that spatial pattern in sap velocity changed from the wet to dry period, while NDVI did not change, the correlation between sap velocity and NDVI was different in the two summers seasons. During the wet summer of 2014, we found a weak to moderate negative correlation, and during the dry summer of 2015, sap velocity and NDVI were uncorrelated. During the dry summer of 2015, water availability (through geology and aspect) likely explained spatial variability in sap velocity, and this soil moisture control of ET was not reflected in NDVI.

4.5 Using NDVI to estimate evapotranspiration

We hypothesised to find a positive correlation between sap velocity and NDVI, but spatially, this was the case only in April. This means that NDVI successfully captured the pattern of sap velocity during the phase of green-up when water was not limited. After green-up, the positive correlation changed into a negative correlation or no correlation. The inconsistent correlation between sap velocity and NDVI would also translate into an inconsistent correlation between transpiration and NDVI, after applying a scaling equation. Various methods however use NDVI to estimate (E)T, among others in evergreen, boreal, and deciduous forests, and assume the two to be positively correlated (Glenn et al. (2010) provide a review). Of these methods, the Kc-NDVI method is used most frequently, and it is shown that including NDVI as a spatio-temporal crop coefficient improves (E)T prediction compared to the conventional use of a crop coefficient in forests (Maselli et al., 2014; Hunink et al., 2017). Other studies however found a weak correlation between NDVI and flux tower transpiration and reported that EVI provides better results in salt cedar and cottonwood dominated stands (Nagler et al., 2005), and boreal forest (Rahman et al., 2001), because the EVI does not saturate as quickly at high LAI (Huete et al., 2002). Therefore we also explored the correlation between sap velocity and the EVI. The results, although in absolute terms different and "less significant", tell a similar story as NDVI – a positive correlation in April, a negative, but not always significant correlation during the rest of the year, and no correlation during the dry summer of 2015.
Compared to our study, earlier studies that found a positive correlation between (E)T and NDVI, encompassed large spatial areas and sometimes multiple land use types. This raises the question if the link between (E)T and NDVI holds on small spatial scale. Methods that use NDVI to estimate ET, including land surface models, should be carefully applied when studying small-scale variability in ET.

NDVI lags behind sap velocity in relation to drought and cannot be used to predict transpiration under dry conditions. A water stress factor has been introduced by several studies to overcome this problem, but this stress factor is not always spatially explicit (e.g. Maselli et al., 2014). Our study showed that, in the studied catchment, a spatially explicit stress factor is required for accurate transpiration prediction under drying conditions, because neither NDVI, nor meteorological conditions capture the spatial variability in ET controlled by geologically induced differences in water availability.

4.6 Using NDVI to scale transpiration

The scaling of water flux measurements across scales is a main challenge in ecohydrology (Asbjornsen et al., 2011; Hatton and Wu, 1995). Scaling *in situ* measurements over a larger area, for example flux tower or sap velocity measurements, is traditionally done by scaling over *in situ* measured biometric parameters such as DBH, basal area, or sapwood area (Čermák et al., 2004). Obtaining these characteristics from satellite images is less resource demanding, can be applied over larger areas, and provides the opportunity to study both spatial and temporal patterns simultaneously. Satellite derived scaling parameters have another advantage over the conventional ones: (semi-)static characteristics are unreliable under the changing conditions that we face for the future, with among others more intense droughts (Cleverly et al., 2016; IPCC, 2012).

This study shows that, in a temperate forest with high LAI and low variability in NDVI and EVI, these indices cannot be used to estimate transpiration or scale sap flux measurements to the stand level. The benefits that satellite derived scaling parameters provide makes it worth exploring other possibilities using remote data to characterise vegetation and (E)T. Reyes-Acosta and Lubczynski (2013) for example used high-resolution images to identify single trees to scale sap flow data to the stand level. Future research could focus on where, and under which conditions tree characteristics control or describe (E)T and whether this relation holds when scaling up to remote sensing derived data on different scales.

5 Conclusions

The aim of this study was to investigate the link between sap velocity and satellite derived NDVI in a temperate forest catchment. We focussed on small-scale variability, both in space and time. A positive correlation between sap velocity and NDVI was expected. Data analysis for two consecutive years led us to the following conclusions:

(a) Temporally, a correlation between sap velocity and NDVI was only found when the entire growing season was considered. Spatially, a positive correlation was found in April, when spatial variability in sap velocity and NDVI was large and reflected an altitude dependent difference in green-up. This means that NDVI did capture the spatial pattern in leaf-out which also affected sap velocity. During the rest of the growing season, a negative correlation was found between sap velocity and NDVI. This negative correlation was significant during half of the studied days. The likely saturation of the NDVI signal in combination with the small spatial variability in NDVI could explain the absence of a positive correlation, but does not explain this negative correlation.

(b) In 2015, during the dry summer period, the spatial correlation between sap velocity and NDVI changed. Variability in sap velocity could not be captured by NDVI. Instead sap velocity was controlled by geology and aspect, likely through their effect on water availability. This shows that a stress factor, used to estimate transpiration during dry periods, cannot always be based on meteorology only, but should include information that reflects the water availability.

(c) The time-variable and inconsistent spatial correlation between sap velocity and NDVI would also translate into an inconsistent correlation between transpiration and NDVI. From this we conclude that NDVI alone cannot describe small-scale temporal and spatial variability in sap velocity and transpiration in a temperate forest ecosystem. Only for temporal scales that cover the whole phenological cycle, NDVI was a significant predictor of transpiration processes. The EVI, which is less sensitive to saturation effects, was also unsuitable as a predictor of transpiration under the studied conditions. Therefore, we suggest that the use of vegetation indices to predict transpiration should be limited to ecosystems and scales where the correlation was confirmed.

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