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THE DETECTION OF DISTURBANCE EFFECTS OF NORWAY SPRUCE (*PICEA ABIES* (L.) KARST.) IN UAV MULTISPECTRAL IMAGERY

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ABSTRACT:

This study analyses spectral separability of Norway spruce (*Picea abies* (L.) Karst.) trees several months after induction of mechanical damage (a simulated wind damage), and one year after the damage – at the beginning of vegetation season and then following a period of drought. Experiment includes sample group of trees (Bent trees) over three plots that underwent static pulling test, therefore simulating survival after storm event. They were compared to a group of trees of the same dimensions that did not undergo static pulling test (Control trees). Spectral reflectance data was collected using unmanned aerial vehicle (UAV) and multispectral sensor. Reflectance of four bands were extracted, converted into indices, and analysed with statistical tests. There were differences in plot response to experiment, as one of the plots failed to show significant difference between groups. Overall, multiple indices proved great results for spectral separation between Control and Bent trees. MACI (Modified Anthocyanin Content Index) was the most consistent in differentiating between groups. Other indices that represent chlorophyll content and photosynthetic activity were also relatively sensitive for stress detection. However, on the contrary to what was expected, period of drought did not seem to affect spectral reflectance of canopies. There was a distinct difference of chlorophyll and anthocyanin content, and photosynthetic activity in sample trees, but these deviations did not manifest in larger scale post drought. Moreover, MACI and GNDVI (Green Normalized Difference Vegetation Index) even reduced mean value gap after the period of low precipitation.

1. INTRODUCTION

Wind in known to cause the most severe natural disturbances in European forests, creating remarkable economic (Hanewinkel et al. 2013; Schwarzbauer and Rauch 2013), ecological (Thürig et al., 2013) and social (Blennow et al., 2013) consequences. Over the last decades, significant amount of damage by volume (Gregow et al., 2017; Lindelow and Schroeder, 2008; Schelhaas et al., 2003; Valinger, Fridman, 2011) has increased along with the frequency of strong wind events and it is expected to continue under the climate change (Forzieri et al., 2021). Furthermore, such negative tendencies might be intensified by other disturbances, such as drought events, which are projected to increase in severity (Grillakis, 2019), creating synergic legacy effects (Csilléry et al., 2017; Cawley et al., 2014). Therefore, the susceptibility of trees to wind damage may become higher if weakened by droughts, whereas the wind damage will increase the vulnerability of trees against droughts and secondary biotic agents that follow (Csilléry et al., 2017; Gardiner et al., 2016).
Norway spruce (*Picea abies* (L.) Karst.), hereafter referred as spruce, is especially vulnerable to drought (Karlsson et al., 1997; Ditmarová et al., 2010) and wind disturbances (Peltola et al., 2000; Krisans et al., 2020). Moreover, spruce is economically significant species, especially in northern Europe, it represented 23% of Europe's total growing stock in 2020 (FOREST EUROPE, 2020). However, its significance in Central Europe has been declining in the past decades, as growing conditions for species is worsening with the climate change (Hanewinkel et al., 2013; Yousefpour et al., 2010).
Wind primarily impacts tree at the crown and forces tree to go into swaying. When force of wind exceeds bending resistance of stem, it breaks, or it is uprooted if force is stronger than root anchorage (Mitchell 2013; Mayer 1987).
However, wind induced damage is not only limited to immediate mortality of tree due to uprooting of stem breaking. Short-term growth reduction due to changes in resource allocation by trees is hypothesised by (Seidl, Blennow, 2012). This means that trees surviving storm are likely to have suffered root damage, therefore are prone to develop root system instead of stem or crown.
Usually, such effects of stressors are detected quite late, in stages when damages are visible. However, discoloration and defoliation can be detectable at very early stages when visual properties of tree crowns are monitored in combination with remote sensing approaches (Rautiainen et al., 2018). Recent advancements in unmanned arial vehicles (UAV) opens new possibilities for efficient, non-destructive, and fairly affordable remote sensing technology application in various fields, including forestry. For example, Huo et al., (2021), Näsi et al., (2015), Abdullah et al., (2019), Minařik et al., (2020) focus their work on mapping or early detection of bark-beetle damaged trees. Multiple studies, including Grulke et al., (2020), Zhang et al., (2008), Kopačková-Strnadová (2021) analyse detection of early stress and changes in leaf pigment, but results vary across studies. An increase in reflectance of red band and decrease in green band in stressed trees has been observed by Lausch et al., (2013). Also Huo et al., (2021) identified an increase in red band reflection, suggesting this band to be good indicator of stress, however he considers that a combination of red band reflection and SWIR (short-waved infrared) band would be more promising in early bark-beetle detection. Other studies (Eitel et al., 2011; Masaitis et al., 2013) consider red-edge band to be very useful for early stress detection in conifers, as it is sensitive to changes in chlorophyll content. When experiencing drought stress, trees tend to close stomata in order to preserve water and, thus, reduce carbon sequestration rate, therefore, changes in photosynthetic activity could be detected with GNDVI (Green Normalized Difference Vegetation Index) (Candiago et al., 2015).
However, there is a lack of research on the detection of stressed trees that have sustained primary failure from wind. Successful application of an early detection of stressed trees could be used for forest management planning and decision making to ensure more effective practices for building resilient forests. For instance, after storm, such technology could help locating and identifying the most susceptible standing trees. As a preventive measure, such trees could be prioritized during thinning in order not to expose the rest of the stand for consecutive disturbances. Therefore, in this study we use Bent trees, that underwent a static pulling test, and Control trees in combination with remote

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sensing techniques to distinguish spectral differences between groups. The aim of this study was to examine simulated wind damage in Norway spruce stands using multispectral images acquired by UAV. We hypothesise that it will be possible to identify Bent trees in multispectral imagery by using vegetation or chlorophyll-based indices, moreover the differences would be more pronounced due to drought.

2. MATERIALS AND METHODS

2.1. Study area

The study was conducted in the middle eastern part of Latvia (Figure 1; A), near Kalsnava parish (Figure 1; B). the experiment took place in spruce stands. There were 3 study sites – two sites on drained mineral soil (*Myrtillosa mel.*) and one on fertile drained mineral soil (*Mercurialiosa mel.*). In the study region, the annual mean air temperature varies from 6 – 7 °C. The highest average temperature is in July, from 17.5 – 18 °C, while the lowest temperature is in January and February with -4.5 °C. Precipitation throughout the year varies from 670 up to 700 mm^{-1} per year (LEGMC, 2021). On the contrary with the values of the whole country, data from the last 30 years suggests that October has the highest precipitation, unlike overall data of the country, which rather suggests July/August. The highest mean wind speed values are during autumn and winter seasons, especially from November to December ranging 3.7 – 4 m s^{-1}. The highest recorded wind speed reached 48 m s^{-1} in 1967. According to a local meteorological station, there was a pre-longed drought period from the end of May till the end of June 2021. This period partly overlapped with the period of extreme summer heat in the second half of June, with an average daily temperature of 21°C, and the mean solar radiation of 256 W m^{-2}.

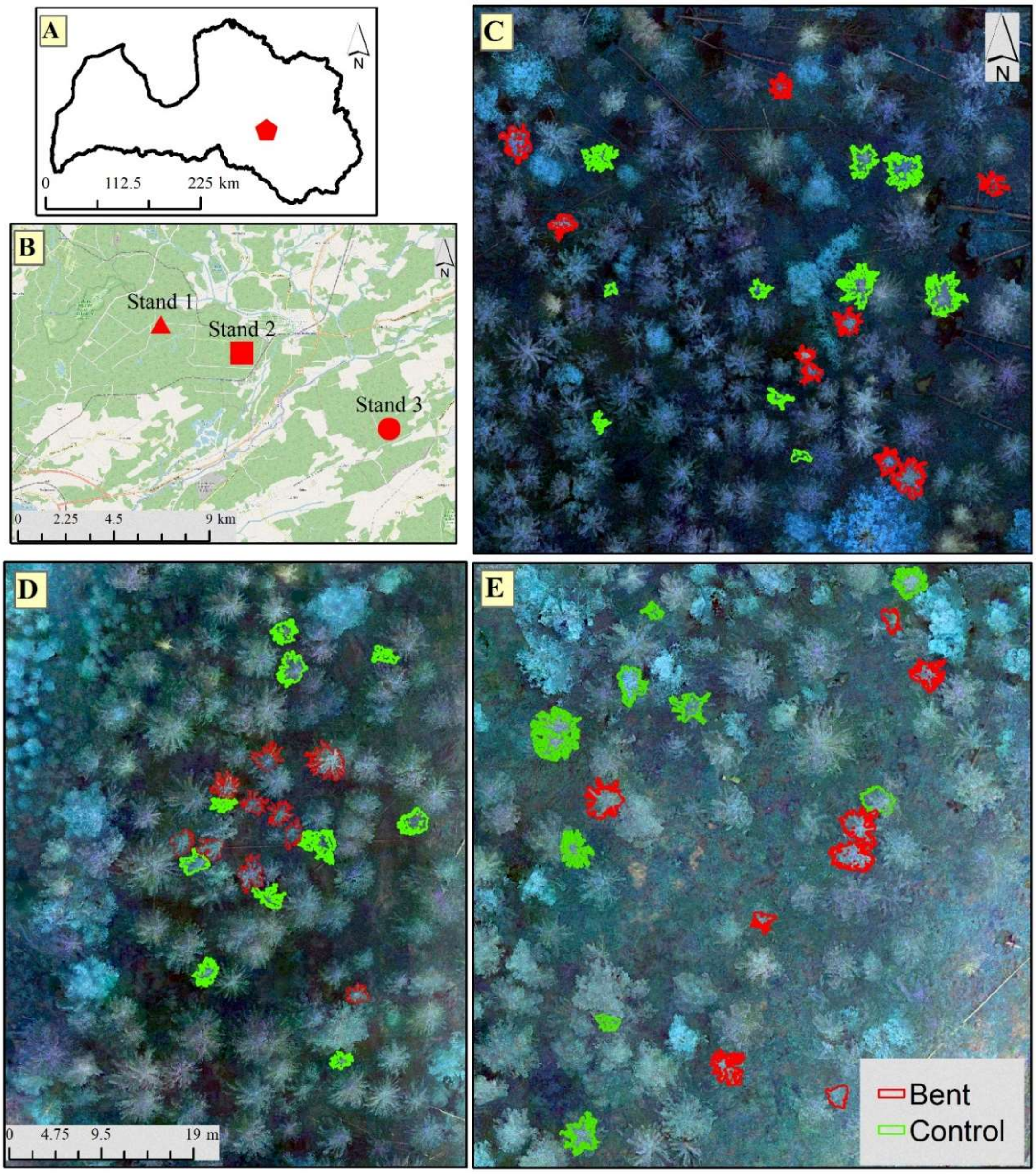

Figure 1. Study area in the middle eastern part of Latvia: (A) Locations of stands in the Latvia; (B) Location of stands on a local scale (data obtained from OpenStreetMap (www.openstreetmap.org)); (C, D and E) Placement and delineation of Bent and Control trees in Stand 1, Stand 2 and Stand 3, respectively. The background ortomosaics were acquired in May 7, 2021 and are showing the combination of Red, Green and RedEdge bands.

Site No.	H, m	DBH, cm	V stem, m^3	Tree crown area, m^2	Bent trees, count	BBMRELATIVE	Soil type	Stand area, ha
1	24.0±1.23*	22.0±1.82	0.41±0.09	4.9±1.56	9	35.1±2.13	saturated mineral	2.18
2	24.7±1.511	24.2±2.58	0.53±0.13	6.9±1.85	10	52.9±3.63	dry mineral	1.14
3	24.2±1.83	24.7±2.14	0.54±0.11	6.99±3.22	9	42.2±5.27	wet mineral	1.20

Table 1. Sample tree parameters. H – mean tree height; DBH – mean diameter at breast height; V – mean stem volume; BBMRELATIVE – relative mean values of primary failure for every timber volume unit. *(± 95% confidence interval)

2.2. Field work and data acquisition

At the beginning of our study, precise GPS coordinates of each tree were measured with Leica GS16 Global Navigation Satellite System (GNSS) receiver and Leica Flexline TS06 total station. During the field work in period from January to March 2020, static pulling of trees was performed by using a cable winch. A cable was tied around an anchor tree and at half height of the tree being pulled, and statical force was applied (Krisans et al., 2020). The sample trees that collapsed upon reaching maximum force, were excluded from further analysis. Our study analyses trees that were able to withstand the maximum applied force. These trees experienced primary failure – deformation of wood fibres (e.g., cracks) in stem and roots (Detter et al., 2013; Krisans et al., 2020). Therefore, this simulates trees that were able to survive wind damage without total collapse. Such trees were grouped together as “Bent” trees (in total 28 trees (Table 1)). For comparison, trees of similar dimensions and that were not tested in pulling test were selected and grouped as “Control” trees (in total 30 trees).
Another part of the field work included four flight campaigns with unmanned aircraft system (UAS). We used a DJI Matrice 210 equipped with SlantRange 3PX multispectral sensor. The sensor is able to sense four wavelengths: green (peak 550 nm, 40 nm wide), red (650 nm, 40 nm), red-edge (710 nm, 20 nm), and near-infrared (850 nm, 100 nm). Chosen ground speed was 4±1 m s^{-1}, while flight altitude was 50 m above ground. First two flights were performed in June and August of 2020, several months after tree pulling tests were performed. The third flight was conducted in May 7, 2021, at the beginning of vegetation season, prior the drought. The fourth flight was performed in July 10, 2021, after the prolonged drought period. Prior each flight at least five ground control points (GCP) were placed across the area of flight, and their precise GPS coordinated were measured by GNSS receiver Leica GS16. The GCPs were used to optimize the sparse cloud and to transform image orientation into geodetic coordinate system LKS 92 (EPGS 3059).

2.3. Data pre-processing

The acquired images were visually inspected and processed using SlantView software (v.2.15.0.2509). The atmospheric and illumination conditions for each frame were adjusted by the ambient illumination sensor, that facilitated further data processing. To derive quantitative information the pixels from false colours to reflectance values were converted and exported into Agisoft Metashape Professional 1.6.4. (Agisoft LLC, 2011) and orthophotos were produced based on the Structure from Motion (SfM) photogrammetric method (Westoby et al., 2012). The green spectrum was used as a default band to align photos, build a dense cloud, generate a digital surface model (DSM) with interpolation and orthomosaics. A radiometrically calibrated and geometrically corrected 4-band multispectral image mosaic was created.

The delineation of individual tree crowns was performed by using the isodata clustering algorithm and Maximum Likelihood Classification (MLC) tools in ArcGis 10.5.0 (ESRI 2017). Isodata cluster allows to characterize the natural groupings of pixels in a list of input bands by creating signature file. Two roughness classes were distinguished separately for high vegetation (tree canopy) and low vegetation (including bare soil). The resulting signature file was used to perform MLC. The classified image was converted into vector format by creating contour lines for high vegetation only. Further, the high vegetation lines were corrected and digitized where it was necessary. For example, adjacent tree crowns were manually separated (Figure 2). Whereas, for the extraction of spectral features the polylines were converted into polygons and multiband values were extracted from each crown (Figure 1. C, D and E).

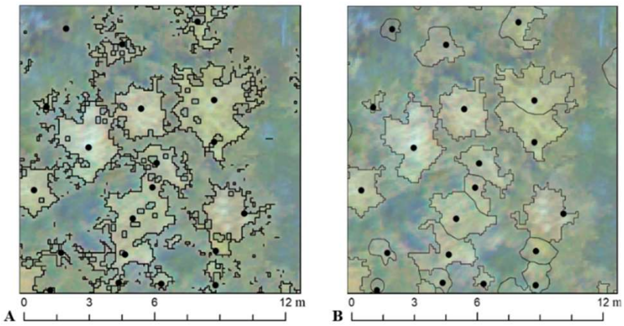

Figure 2. An example of crown delineation: (A) Derived contour lines from Maximum likelihood classification for tree crowns; (B) Corrected and digitized polylines. (Black dots representing tree stem location).

2.4. Indices and statistical analysis

The mean values of spectral features of each crown were extracted and further processed in R 4.0.4. (R core team, 2021). To minimize the potential confounding effects of single spectral bands due to different factors (such as sun angle, viewing angle, the atmospheric composition and canopy background variation (Jensen, 2009)) the initial status of damages (the differences in canopy reflectance between Bent and Control trees) were assessed by using vegetation indices. Multiple vegetation and chlorophyll-based indices existing in the literature that are used for the early stress detection (Abdullah et al., 2019; Minařik et al., 2020) were calculated and examined in linear mixed effects regression analysis. Vegetation indices with no meaningful results were removed from further analysis and only the most suitable ones were selected for detailed analysis (Table 2.).

INDEX	Equation	Reference
GNDVI	(NIR - Green)/(NIR + Green)	Cicek et al., 2010

MACI	NIR / Green	Gitelson et al., 2009
CI	(NIR / RedEdge) – 1	Gitelson et al., 2009
NDRE	(NIR - RedEdge) / (NIR + RedEdge)	Tilling et al., 2007

Table 2. Indices and equations for calculation

To test our hypothesis, we created linear mixed-effect model where the means of each crown were used as dependent variables, groups Bent or Control and flight as independent variables, and to deal with possible pseudo-replication – stand was used as a random factor. The test was performed by using "*nlme*" package in R (Pinheiro and Bates, 2000). The package "*lsmeans"* was used to calculate predicted means for both groups Control trees and Bent trees (Lenth and Herve 2015). The contrasts of pairwise comparisons among the predicted means were calculated with Tukey's HSD post-hoc tests, with significance level p-value<0.05. Multicollinearity between vegetation indices was tested and the best models were selected by Akaike`s Information Criterion (AIC) (Burnham, 1998).

3. RESULTS AND DISCUSSION

3.1. The identification of bent trees in multispectral images

In our study, we simulated the impact of strong wind in non-destructive manner by testing the mechanical stability of Norway spruce trees. We used data from tree pulling test in order to correlate pulling results with index values. However, *rcor.test* showed no correlation between any index and pulling measurements.

The results of linear mixed-effect model indicated statistically significant effect ($p < 0.001$) of groups Bent and Control and flight. The most important vegetation indices explaining spectral differences between Bent and Control groups were GNDVI, MACI, CI, NDRE indices (Figure 3). Our models showed considerable importance of total explanatory power – for NDRE index the R^2 was 0.42 and RMSE was 0.078 ($p<0.001$), for GNDVI index the R^2 was 0.45 and RMSE was 0.081 ($p<0.001$), for MACI index the R^2 was 0.51 and RMSE was 0.408 ($p<0.001$) and for CI index the R^2 was 0.51 and RMSE was 0.437 ($p<0.001$). Our results are consistent with other researches (Campbell et al., 2004, Masaitis et al., 2013), which suggested that the ratios (vegetation indices) from sensitive regions (670-705 nm) and a band from region with lower sensitivity (e.g. NIR) provided the highest potential in spectral separability for an initial status of damages in Norway spruce canopies.

Analysing the differences for the spectral indices, we found similar patterns with the lowest values for all indices in August 2020 (Figure 3). We suspect that such reduction in values may be caused by shadows and lighting conditions (direct sunlight) during the image acquisition in August 2020 on Site 3. The GNDVI appeared to be significantly ($p<0.001$) greater for Control trees than for Bent trees in all flights, by 8.1 % on average (Table 3). As GNDVI is based on photosynthetic activity, the differences in the June 2020 might be linked to the mechanical damage of root system, as mechanical pulling was done only several months ago. Similarly, the physiological processes of trees that survive storms have been negatively affected even if there are no visible damages to crown or stem, but only to the roots (Stokes, 1999). In such case water uptake is disturbed and photosynthetic activity is lower (Reubens et al., 2009). After roots are damaged, trees may allocate more water and carbon to replace damaged roots, thus the large difference.

Significant ($p<0.001$) differences between Bent and Control trees were found also for MACI index. Our result suggested that the mean values of MACI were on average 8.2% higher for Control trees than for Bent trees (Table 3.). The initial decline of MACI values for Bent trees can be explained with anthocyanin pigment content, that generally develops within plants with the presence of stressors (i.e., pests, droughts) (Neill and Gould, 1999, Landi et al., 2015). In addition, we noticed that canopies of Control trees have higher absorption in visible light range and a higher reflectance in NIR band, that resulted in larger difference between bands. Meanwhile, stressed trees had lower difference between these bands due to the presence of stressors, that lowers absorption in visible light and increases absorption in NIR band. In practice our model showed a significantly higher absorption ($p=0.11$) of green Band for Control (16.5±1.18), than for Bent trees (17.8±1.22). However, NIR values for Bent trees were fairly similar (Control – 41.2±1.75; Bent – 41.2±1.89).

Flight	GNDVI, %	MACI, %	CI, %	NDRE, %
June 2020	7.9	8.3	10.0	5.3
August 2020	9.7	9.3	13.6	6.6
May 2021	7.5	7.6	11.2	5.4
July 2021	7.4	7.7	9.0	4.8

Table 3. The differences between groups Control and Bent tree in the mean values of selected vegetation indices.

The results of CI index for both groups were lower during the flight in May 2021, when compared with flights in June 2020 and July 2021 (Figure 3; CI). That could be related to the beginning of vegetation season, as CI detects chlorophyll content, nevertheless, Control trees showed significantly ($p < 0.001$) higher CI values for all flights than Bent trees, by 10.9% on average (Table 3).

Our results suggested that the NDRE index could also be used for detection of chlorophyll content and stress detection. We found significantly ($p<0.001$) higher NDRE values for Control trees than it was detected for Bent trees, by 5.5 % on average (Table 3).

Lastly, trees that sustain wind damage without a collapse, such as Bent trees in this study, are likely to be more susceptible to drought, fungal or pest attacks (Gardiner et al., 2013). Therefore, we expected to see an increase in deviation between groups in the values of the vegetation indices, following period of drought. However, CI was the only one that showed increased gap between mean values after drought (Figure 3). However, NDRE, which also detects chlorophyll content, did not follow the same tendency, such outcome is in contrast to other studies (Eitel et al., 2011; Masaitis et al., 2013), which identified red-edge to be the most sensitive for early stress detection in spruce. MACI (anthocyanin content) and GNDVI (photosynthetic activity) had similar tendencies over the course of study. For both indices Control group stayed practically unchanged between flights, with moderate increase toward the post drought flight. Meanwhile, Bent trees had significantly lower values than Control in May – at the beginning of vegetation period, but by the next flight in July, differences between groups decreased. This indicates a slower and later start of vegetation season for Bent trees.

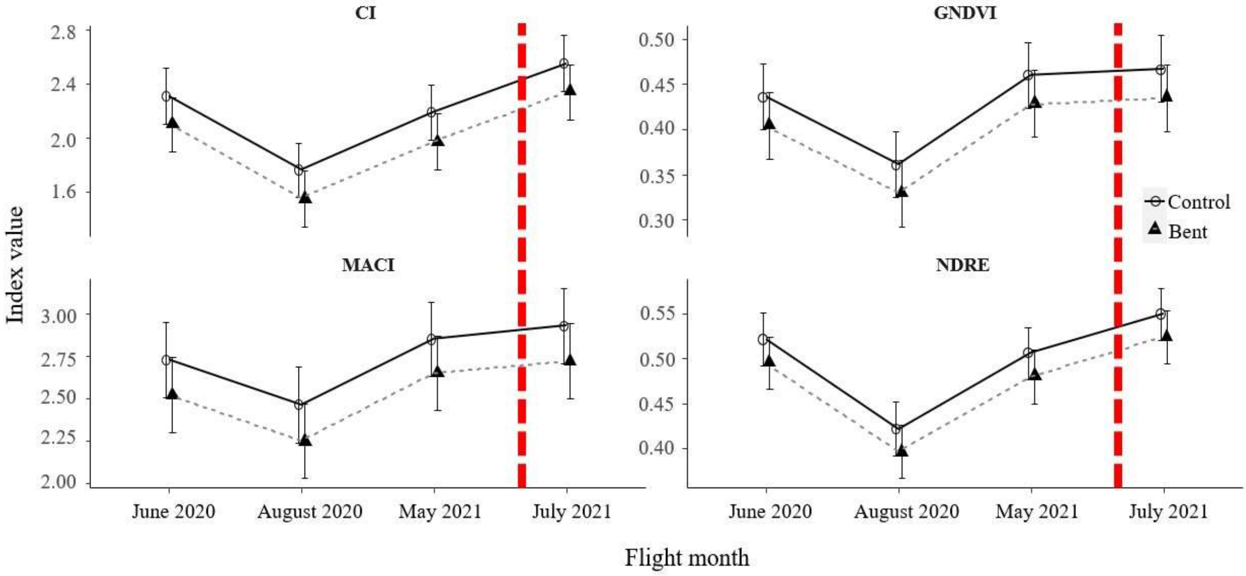

Figure 3. Values of indices with $p<0.05$ (*lmer*), compared between groups and flights (±95% confidence interval). (The dashed red line shows the pre-longed drought at the beginning of summer in 2021)

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CONCLUSION

Our proposed hypothesis was partly true, it was possible to identify differences between Bent trees and Control trees. However, the differences in values did not increase after period of drought. Moreover, MACI and GNDVI had larger deviation in results at the beginning of vegetation season rather than after the drought. This suggests that Bent trees have distinctly lower chlorophyll and anthocyanin content, and lower photosynthetic activity. However, drought did not affect Bent trees more than Control trees. We recognize that our sample group was quite small, but we see a potential in application of multiple indices in stress detection. Therefore, further studies on larger sample group and with different precipitation and temperature conditions are necessary.

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