Differentiating Acute and Chronic Stress in Norway Spruce using Hyperspectral and Thermal Remote Sensing in Experimental Plots

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Abstract

Norway spruce forests across Europe are increasingly threatened by acute and chronic stressors, particularly thermal exposure and drought, exacerbated by climate change. This study investigates the physiological and spectral responses of spruce trees under experimentally induced stress using high resolution thermal and hyperspectral remote sensing from UAV and aircraft platforms. Field experiments were conducted in Slovakia and the Czech Republic across three plot types: edge exposed (acute thermal stress), roofed (chronic drought stress), and unmanipulated controls.
By integrating remote sensing data with sap flow, VOC emissions, and soil microclimate measurements, we show that acute stress from sudden edge exposure triggers rapid physiological responses, including increased transpiration, elevated crown temperatures, and distinctive VOC profiles. In contrast, chronic drought stress, simulated through rainfall exclusion, leads to sustained reductions in sap flow, lower water availability, and declines in key spectral indices such as MRENDVI and NDWI. Bark beetle attacks occurred only in drought stressed trees, suggesting a link between prolonged physiological decline and pest vulnerability.
Generalised Additive Models revealed that crown temperature, soil water potential, and canopy structure strongly influence sap flow, while thermal traits were shaped by canopy density and solar radiation. Remote sensing data captured these relationships, enabling early detection of stress before visible symptoms emerged.
Our findings confirm that thermal and hyperspectral imaging, supported by ground truth data, can reliably distinguish between acute and chronic stress in Norway spruce. This multi sensor approach supports proactive forest health monitoring and early intervention against bark beetle outbreaks under changing climatic conditions.

1. Introduction

European coniferous forests, particularly those dominated by Norway spruce (*Picea abies*), are increasingly vulnerable to climate-induced stress factors such as prolonged drought, heatwaves, and abrupt canopy openings resulting from management or disturbance. These pressures impair water transport, disrupt physiological stability, and reduce tree resilience, contributing to a rise in bark beetle *Ips typographus* outbreaks across Central Europe. Two primary stress pathways, chronic drought and acute thermal stress from edge exposure, pose a growing threat to forest health. Although both can lead to physiological decline, they differ substantially in timing, spatial extent, and the mechanisms by which they impact tree function.

Detecting these stress responses before visible symptoms emerge is essential for proactive forest management. Remote sensing technologies, especially thermal and hyperspectral imaging, have emerged as powerful tools for early stress detection by capturing indicators of water status, canopy temperature, and metabolic shifts. However, differentiating between stress types using remote data remains a major challenge due to overlapping symptoms, subtle physiological nuances, and site-specific variability. Acute and chronic stressors differ not only in intensity and duration, but also in their spectral and thermal signatures, which can vary with canopy structure, stand microclimate, and phenological stage.

Addressing these complexities requires integrated approaches that combine remote sensing with ground-based ecophysiological measurements. Recent advances have underscored the importance of linking tree-level processes, such as sap flow, crown temperature, and volatile organic compound (VOC) emissions, to canopy-scale signals observable in spectral reflectance and thermal imagery. Structural attributes like crown density, trunk diameter, and solar exposure also influence how stress manifests in remote sensing data. Controlled experimental designs that isolate specific stressors are essential for identifying reliable indicators of early decline and for improving stress-type classification in operational monitoring systems.

This study evaluates the use of airborne and UAV-based thermal and hyperspectral remote sensing, coupled with field-based physiological measurements, to differentiate between acute and chronic stress responses in mature Norway spruce trees. Experiments were conducted at two research sites located in managed forest areas: Očová (Slovakia) and Kostelec nad Černými lesy (Czech Republic). Trees were assigned to three treatment groups: edge-exposed (simulating acute thermal stress), roofed plots (simulating chronic drought through rainfall exclusion), and control trees located in closed-canopy forest interiors. The experimental setup enables comparison of stress responses under contrasting environmental pressures while controlling for confounding stand variables.

We hypothesised that acute thermal stress would trigger rapid but potentially reversible physiological responses and elevated canopy temperatures, while chronic drought stress would result in suppressed transpiration and spectral changes reflecting water deficiency. By integrating high-resolution remote sensing with

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ground truth data on water fluxes, canopy structure, and metabolic indicators, we aim to identify robust, stress-specific remote indicators that support early detection and management of declining spruce stands.

2. Methods

2.1 Remote Sensing Campaigns

In both Očová and Kostelec nad Černými lesy, UAV data were collected using the same platform: the SwissDrones SDO 50, a heavy-lift vertical take-off and landing (VTOL) unmanned helicopter (Fig. 1). This UAV is capable of long-endurance flights and carrying advanced scientific payloads. It was equipped with a DigiTHERM thermal camera operating in the 7.5–13.5 µm range, producing thermal images with approximately 10 cm spatial resolution and image sizes of around 40×60 m. The UAV system also used a Novatel OEMV1 GPS/INS unit for precise positioning. UAV flights were conducted under clear-sky conditions on 7 August 2020, between 11:27 and 11:33 a.m., to capture maximum thermal contrast across canopy surfaces.

Figure 1. The SwissDrones SDO 50, a heavy-lift vertical take-off and landing unmanned helicopter used for UAV data collection in Očová and Kostelec nad Černými lesy study areas.

For airborne remote sensing, conducted exclusively at the Kostelec site, a Cessna 208B Grand Caravan aircraft was used. The aircraft was equipped with a CASI-1500 hyperspectral sensor (VNIR range), a SASI-600 sensor (SWIR range), a TASI-600 sensor (thermal infrared), and a Leica ALS70-CM LiDAR scanner. These sensors were integrated to allow simultaneous data acquisition. The thermal and hyperspectral systems provided detailed reflectance and temperature data, while LiDAR captured high-density point clouds for structural analysis. The hyperspectral data were atmospherically corrected and georeferenced to the LiDAR data, enabling precise tree-level comparisons. This multi-sensor platform allowed comprehensive assessment of canopy condition, structure, and stress indicators across the entire study area.

2.2 Field Instrumentation and Data Collection

To characterise the physiological responses of Norway spruce to different stress conditions, several ground-based measurements were conducted. Sap flow was continuously monitored using EMS81 thermal dissipation sensors (EMS, Brno, Czech Republic) installed at breast height on the main trunk of each sampled tree. Measurements were recorded at 10-minute intervals, excluding nocturnal values due to negligible flow rates, and subsequently averaged to obtain daily sap flow values. VOCs were collected from sun-exposed branches using the dynamic headspace sampling method (Fig. 2). Air was drawn through Tenax TA sorbent tubes to trap emitted VOCs, which were later analysed using gas chromatography coupled with mass spectrometry (GC-MS) to determine compound composition and emission profiles. Soil microclimatic conditions were assessed by installing sensors at depths of 15 and 30 cm to measure soil water potential and temperature (Marešová et al. 2020). These measurements provided critical context for interpreting tree physiological behaviour under both acute thermal and chronic drought stress scenarios.

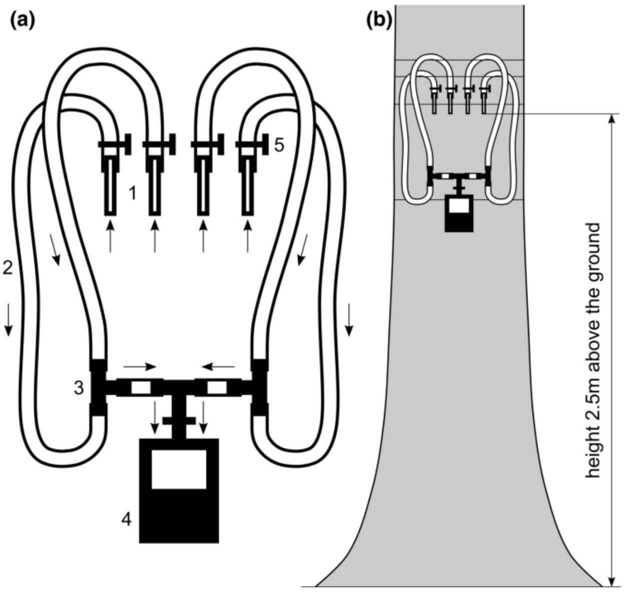

Figure 2. Schematic of the device setup used for volatile organic compound (VOC) air sampling. Arrows indicate the direction of airflow: ambient air was drawn through four Tenax TA sorbent tubes (1), passed via Tygon hoses (2) and plastic splitters (3), and directed into the sampling pump (4). A screw clamp (5) was used to standardise airflow across all sampling lines. (b) Placement of the sampling pumps on Norway spruce trees in the forest (Marešová et al., 2020).

2.3 Plot Design Details

The experimental design was based on individual-tree sampling across two research sites, with each tree serving as an independent sampling unit rather than being grouped within fixed-area plots. Trees were selected from managed Norway spruce stands approximately 50 to 60 years old. Selection criteria included uniformity in diameter at breast height (DBH), height, and overall health to minimise intra-treatment variability. Treatments were applied at the tree level and defined by surrounding stand conditions, enabling a tree-centric approach that supported both physiological monitoring and spatial integration with remote sensing data. Three treatment types were established: edge-exposed trees representing acute thermal stress, roofed trees simulating chronic drought stress, and unmanipulated control trees located within closed-canopy forest interiors.

At the Očová site in central Slovakia, only edge and control treatments were implemented. Edge plots were created by clear-cutting adjacent forest on the southern side to expose tree crowns to increased solar radiation and wind, particularly during midday hours, thereby inducing acute thermal stress (Marešová et al.

2020). Control trees were located at least 50 to 70 m from any forest edge within continuous canopy cover. No roofing structures or soil modifications were applied. UAV-based thermal and RGB imagery was acquired to capture canopy temperature dynamics over the course of the day.

The Kostelec nad Černými lesy study area in the Czech Republic included all three treatment types (Fig. 3). Roofed plots were established by suspending transparent polyethylene foil at approximately 2.5 metres above ground level, allowing light penetration and air exchange while excluding direct rainfall. These structures were maintained from early spring to late autumn, and soil water potential measurements confirmed long-term reductions in moisture, effectively simulating drought stress. Edge plots were created using a clear-cutting method similar to that used in Očová, while control trees remained under closed-canopy conditions without intervention. Both UAV and airborne remote sensing campaigns were conducted at this site, enabling multi-scale comparisons across treatment types.

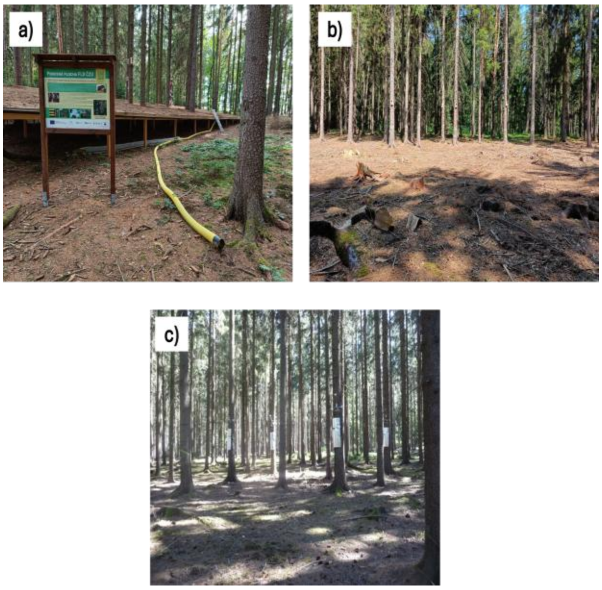

Figure 3. Visual representation of roof sub-plots (panel a), edge sub-plots (panel b) and control sub-plots (panel c) in each of five mature (70 – 90 years) forest stands in Kostelec nad Černými lesy, Czech Republic (Pivovar et al., 2025).

2.4 Data Processing and Analysis

LiDAR data were processed using "lidR" package in R to generate pit-free CHMs. Crown parameters (height, area, density) were derived. Hyperspectral images were converted to surface reflectance and used to compute Enhanced Vegetation Index (EVI), Normalised Difference Water Index (NDWI), Modified Red Edge Normalised Difference Vegetation Index (MRENDVI), and Drought Water Stress Index (DWSI). Thermal data were corrected for emissivity and atmospheric conditions. Tree crowns were delineated manually or using object-based image analysis and linked with physiological measurements.

All remote sensing datasets were spatially aligned using GPS and LiDAR-derived crown positions. Tree crowns were delineated manually in the RGB and thermal imagery. Crown-level statistics were extracted for vegetation indices (EVI, NDWI, MRENDVI, DWSI) and thermal variables, particularly mean and maximum crown surface temperature. Spectral indices were calculated from atmospherically corrected hyperspectral data. Canopy structure metrics, such as height, crown projection area, and density, were derived from LiDAR point clouds using the "lidR" R package.

Statistical comparisons across treatment groups were performed using Kruskal-Wallis tests followed by Dunn's post hoc analysis to assess significant pairwise differences. To evaluate the influence of biotic and abiotic factors on physiological processes, we developed Generalized Additive Models (GAMs) for two primary response variables: sap flow and crown surface temperature. Predictor variables included DBH, soil water potential, canopy density, radiation load, and crown temperature. GAMs were selected for their ability to model non-linear relationships and interactions using smooth splines, with model performance evaluated by adjusted R^2 and residual diagnostics.

2.5 Hyperspectral Data Processing and Spectral Analysis

In addition to the multi-sensor airborne platform, high-resolution hyperspectral imagery was central to stress detection and analysis. Data from the CASI-1500 (VNIR: 380–1050 nm) and SASI-600 (SWIR: 950–2450 nm) sensors were acquired over six campaign dates between June 2022 and August 2023 (Fig. 4). Raw data underwent comprehensive preprocessing using the GeoCor 5.6.3 software. This included radiometric calibration (scatter light correction, smear correction, second-order light correction, bad pixel interpolation, and residual correction), orthorectification using LiDAR-derived DSMs, and atmospheric correction based on radiative transfer models. Data were georeferenced using GNSS/IMU navigation data and resampled to UTM Zone 33N (ETRS-89). Final surface reflectance values were derived and mosaicked using nadir-most pixel selection.

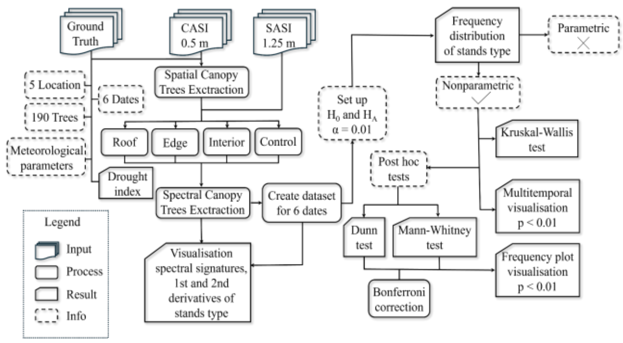

Figure 4. Visualization of the study design (Pivovar et al., 2025).

To ensure spectral consistency, reflectance data from spectral regions known for atmospheric absorption or sensor overlap were excluded from the analysis (specifically: 950–1000 nm, 1350–1500 nm, 1800–1950 nm, 2350–2500 nm, and 1000–1080 nm). Tree crowns were delineated manually using ENVI 5.2 by extracting sunlit canopy regions from RGB images and aligned hyperspectral data (Fig. 5). Each tree crown was associated with a GPS-tagged centroid to maintain correspondence across dates. Reflectance profiles for each crown were averaged, and their first and second spectral derivatives were computed using Savitzky-Golay filtering (polynomial order 2, frame length 7) to highlight subtle stress-related spectral differences (Pivovar et al., 2025).

Statistical analysis of spectral differences among treatment types (edge, roofed, control) was performed for raw reflectance values and their derivatives using non-parametric Kruskal-Wallis tests, followed by pairwise Dunn's and Mann-Whitney U tests (with Bonferroni correction) to assess spectral separability across all dates and wavelengths. Kernel density estimation (KDE) was applied to assess distribution characteristics. Multi-temporal analysis was conducted to track spectral shifts and identify phenologically sensitive periods for stress detection, with particular focus on red-edge, NIR, and SWIR regions.

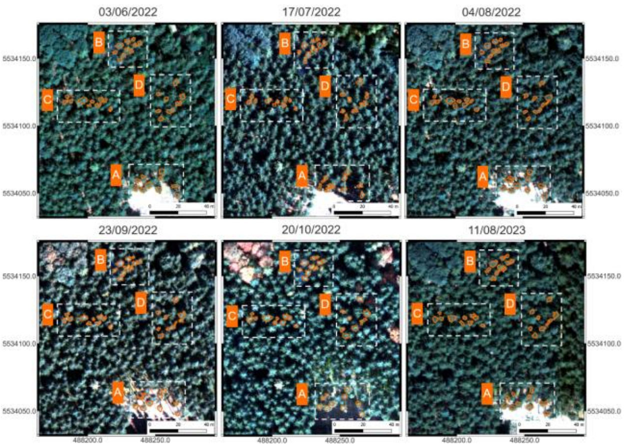

Figure 5. RGB image from CASI sensor for each date in Location 5. Sub-plot A (Forest edge – Acute stress), sub-plot B (Roof – Chronic drought stress), sub-plot C and D (Control plots). EPSG: 32633 (WGS 84 / UTM zone 33N) (Pivovar et al., 2025).

Meteorological data were integrated to contextualise spectral changes. Daily temperature, humidity, precipitation, and solar radiation from a nearby weather station (Ondřejov, ~10 km from site) were used to calculate a drought index using the TANABBO model. This index informed interpretation of observed stress patterns in spectral data.

3. Results

Remote sensing and physiological data revealed clear distinctions between stress treatments. In forest edge plots, trees showed elevated crown and bark temperatures, with sun-exposed bark surfaces reaching up to 40 °C. Sap flow rates in these trees were significantly higher than in interior controls, particularly during midday, with peak values coinciding with periods of maximum solar radiation (Marešová et al., 2020). VOC emissions were elevated in edge-exposed trees, with notable increases in total emission rates and altered compound composition. Monoterpenes such as α-pinene, β-pinene, limonene, and myrcene were among the most abundant compounds recorded. Edge trees also exhibited higher proportions of sesquiterpenes and oxygenated monoterpenes. Diurnal bark temperature profiles in these trees showed greater fluctuations, with consistently higher afternoon surface temperatures compared to interior trees. Spectral reflectance data revealed increased near-infrared (NIR) reflectance in edge trees relative to controls, particularly in wavelengths above 750 nm.

Hyperspectral remote sensing data analysis provided detailed insights into the physiological differentiation of Norway spruce trees under chronic drought (roofed plots) and acute thermal stress (edge plots) (Fig. 6). Roofed plots in Kostelec nad Černými lesy showed a very different response. Trees under long-term drought conditions had markedly reduced sap flow, the lowest soil water potential, and elevated but less extreme crown temperatures compared to edge plots (Karpov et al., unpublished). These trees were the only ones attacked by *I. typographus* during the monitoring period. Spectral indices such as MRENDVI and NDWI were significantly lower in roofed plots, indicating reduced water content and potential decline in foliage health. Attacked trees had even lower MRENDVI values, distinguishing them from non-attacked counterparts. Control plots maintained stable conditions with lower crown temperatures, high sap flow rates, and optimal spectral index values, serving as a physiological baseline.

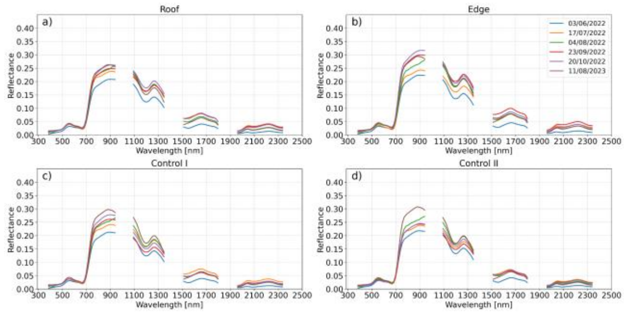

Figure 6. Shape of the spectral curves for Norway spruce across sub-plots a) Roof, b) Edge, c) Control I, and d) Control II, for various observation dates, calculated as the average of individual test areas 1 to 5 (Pivovar et al., 2025).

Across six aerial imaging campaigns in 2022 and 2023, statistically significant spectral separability was observed between stressed and control trees in key wavelength regions (Pivovar et al., 2025). The most diagnostic wavebands included the red (669.58 nm), near-infrared (854.96 nm), and short-wave infrared (1557.5 nm and 2082.5 nm), with pronounced differences emerging particularly in late summer and autumn. Trees under chronic drought showed consistently higher SWIR reflectance, indicative of reduced needle water content, while acutely stressed trees exhibited variable NIR reflectance, increasing in October but declining in August 2023 suggesting seasonally dynamic structural responses in the canopy. First and second spectral derivative analyses further enhanced discrimination between treatment groups, revealing that chronic and acute stress induced different spectral patterns. The red edge region (~720–730 nm) shifted in response to changes in chlorophyll concentration, while SWIR bands revealed stress-related changes in water status and leaf chemistry. Statistical analyses, including the Kruskal-Wallis test and Mann-Whitney U tests with Bonferroni correction, confirmed that spectral reflectance differed significantly across treatments at nearly all wavelengths, with the strongest separability between chronic and acute stress observed in August and September. These results highlight the capacity of hyperspectral imaging not only to distinguish stress intensity but also to differentiate the nature of physiological stressors, enabling early detection of stress responses potentially linked to bark beetle susceptibility (Pivovar et al., 2025).

GAMs showed that trunk diameter (DBH), crown surface temperature, and soil water potential were strong predictors of sap flow, with an adjusted R^2 of 0.48. Sap flow was positively associated with DBH and soil water potential, while crown temperature had a negative effect. The relationship with DBH was non-linear, with diminishing returns in larger trees. Sap flow peaked at moderate crown temperatures (~28–30 °C) but declined steeply at higher values. Crown temperature modelling (adjusted $R^2 = 0.65$) identified canopy density, shortwave solar radiation, and sap flow as the strongest predictors. Higher canopy density was associated with lower crown temperatures, while increased solar radiation led to elevated crown warming. The effect of sap flow on crown temperature was non-linear, with cooling evident primarily at moderate to high flow rates. Additional predictors included tree height and sky view factor, which both showed weaker but significant contributions. Models also revealed seasonal interactions, with the strength of predictors varying over time: for instance, the cooling effect of sap flow was strongest during late summer under high evaporative demand (Karpov et al. 2025).

4. Discussion

The results clearly demonstrate that acute and chronic stress produce distinct physiological and remote sensing signatures in Norway spruce. Trees subjected to thermal stress showed rapid but potentially reversible responses, including increased transpiration, elevated volatile organic compound emissions, and distinct thermal gradients across the canopy (Marešová et al., 2020). These responses were effectively captured using unmanned aerial vehicle thermal and multispectral imaging, highlighting the sensitivity of remote platforms to early physiological change.

In the forest edge plots, where trees were exposed to sudden increases in solar radiation, thermal imaging in the 8 to 14 micrometre range consistently recorded elevated crown surface temperatures, particularly during midday periods. At the Očová site, these trees also exhibited marked increases in sap flow and a notable rise in emissions of monoterpenes such as α-pinene, β-pinene, limonene, and myrcene, consistent with previously reported stress-related VOC profiles (Marešová et al., 2020). Elevated transpiration in these trees likely served to buffer rising canopy temperatures but also coincided with increased evaporative demand imposed by the open stand edge. VOC emissions were not only higher in absolute terms but also showed altered ratios between monoterpenes and sesquiterpenes, a shift which may affect host recognition and aggregation behaviour in *I. typographus*.

Bark surface temperatures on sunlit sides frequently exceeded 35–40 °C, a thermal load that may act as both a physiological stressor and a volatile emission amplifier (Marešová et al., 2020). These effects were strongly diurnal, with maximum bark and canopy temperatures occurring between 12:00 and 14:00, aligning with peak VOC emissions and sap flow rates. The spectral responses in the near-infrared region observed in this study are consistent with canopy-level structural or pigment changes reported at edge locations, potentially reflecting early degradation or photoprotective adjustments. These findings illustrate that the forest edge functions as a microclimatic stress zone, amplifying thermal load and triggering coordinated changes in water transport, volatile metabolism, and canopy radiative properties.

In contrast, roofed trees subjected to chronic drought stress demonstrated a different trajectory. Hyperspectral data from the shortwave infrared region between 1557 and 2082 nm indicated decreased foliar water content and pigment degradation. These trees consistently showed reduced sap flow and gradual canopy warming. Thermal data revealed a prolonged, moderate increase in crown temperatures, consistent with water limitation rather than rapid heat stress (Kozhoridze et al. 2023; Pivovar et al., 2025). Spectral indices such as NDVI and MRENDVI were significantly lower in roofed trees, reflecting persistent water stress and helping to distinguish drought from thermal exposure. Spectral separability between roofed and edge-exposed trees was strongest in the SWIR and red-edge regions, confirming the utility of specific wavebands for differentiating stress types (Pivovar et al., 2025). Time-series analysis revealed that separability peaked during late summer and early autumn, particularly in the 669, 855, 1557, and 2082 nm bands, underscoring the importance of phenological timing in stress detection.

Control trees within undisturbed stand interiors maintained stable physiological function. They exhibited high sap flow rates, low crown temperatures, and neutral reflectance patterns across the spectral bands. No elevation in terpene emissions was detected, and thermal imaging confirmed efficient transpirational cooling. These trees served as essential physiological baselines, offering a clear contrast to the stressed conditions observed in edge and roofed treatments.

These findings demonstrate that forest edge exposure results in rapid, heat-driven changes in physiological and chemical function, while drought-stressed trees undergo slower, cumulative decline. Both forms of stress were detectable before the onset of visible symptoms, reinforcing the utility of hyperspectral and thermal sensors for early diagnosis. The application of first- and second-order spectral derivatives improved the separability of stressed trees and revealed consistent patterns in both acute and chronic responses (Pivovar et al., 2025). These derivative features were particularly informative in red-edge and SWIR bands, providing subtle indicators of structural or biochemical shifts that were not visible in raw reflectance spectra alone.

Only trees under chronic drought conditions experienced natural bark beetle attack during the monitoring period. This observation underscores the link between long-term physiological decline and increased susceptibility to biotic disturbance. Lower spectral index values in attacked trees, particularly in MRENDVI, suggest that hyperspectral imaging may offer early indicators of pest vulnerability, enabling targeted surveillance and mitigation efforts. The spectral signatures associated with attacked trees showed significant overlap with drought-stressed but non-attacked trees, supporting the idea of a physiological tipping point beyond which biotic risk escalates.

The results from GAMs support the hypothesis that both environmental factors and structural crown traits exert significant control over sap flow and canopy temperature. Variables such as trunk diameter, soil water potential, canopy density, and solar radiation were identified as key predictors, with non-linear interactions captured effectively through spline-based modelling (Karpov et al., 2025). The effect of sap flow on crown temperature was strongest at intermediate flow rates, suggesting a non-linear cooling response (Kozhoridze et al. 2024). Seasonal shifts were also evident, with predictor importance varying between early and late summer. These patterns highlight the importance of dynamic models that can accommodate temporal variation in physiological control mechanisms.

The combined use of UAV and airborne campaigns enhanced the spatial and temporal resolution of observations. The high-resolution UAV imagery at Očová enabled detailed analysis of localised stress conditions, while the aircraft-based platform at Kostelec allowed broader spatial assessment across multiple treatments. This dual-scale approach facilitated cross-validation of results and increased confidence in the identified stress signatures. The experimental manipulation of edge exposure and rainfall exclusion created a robust comparative framework, revealing the contrasting mechanisms and trajectories of acute and chronic stress in Norway spruce under changing climatic conditions.

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5. Conclusions

This study confirms that remote sensing platforms can reliably detect and differentiate between acute and chronic stress in Norway spruce forests. The UAV-based monitoring at Očová effectively captured thermal stress effects at high spatial resolution, while the aircraft-based observations at Kostelec provided more comprehensive data across drought-stressed and control plots.

Key physiological indicators such as sap flow and VOC emissions, when linked to remote sensing indices, offer a powerful approach to early forest health diagnostics. The experimental design, featuring both edge and roofed plots, enabled clear comparison of stress dynamics. Our results highlight the importance of targeted monitoring strategies, where UAVs can be deployed for high-resolution assessments and aircraft for broader coverage.

Early detection of vulnerable trees through hyperspectral and thermal data supports more proactive forest management and may help mitigate large-scale bark beetle outbreaks under future climate scenarios.

Acknowledgments

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