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Mapping Relative Health of Individual Spruces with Multispectral Drone

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Abstract

Nitrogen is a key nutrient influencing photosynthesis, growth, and resilience in Boreal forest ecosystems. As nitrogen deficiency becomes more prevalent due to anthropogenic pressures, efficient and scalable methods for detecting forest stress are increasingly needed. This study explores the feasibility of using drone-based imaging and spectral data to assess the health status of *Picea abies* (Norway spruce), with a particular focus on identifying signs of nutrient deficiency and general stress. We proposed and validated three hypotheses: (1) the spectral reflectance of individual spruce needles reveals health status, (2) drone-based 3D mapping can effectively identify and map individual spruce trees, and (3) multispectral drone imagery can detect health differences between trees. Our study was conducted on an 18-hectare spruce-dominant test site in Savonranta, Finland. High-resolution 3D models were created using UAV imagery, allowing for the detection and spatial mapping of over 3,000 individual spruce trees. Needle-level spectral measurements showed clear reflectance differences between healthy trees, nitrogen-deficient trees, and those under additional stress. Multispectral drone data further supported these findings, with particularly strong differentiation observed in the red edge and near-infrared bands. These results demonstrate that drone-based remote sensing techniques can detect subtle physiological changes in trees and offer a scalable approach to forest health monitoring. The integration of in-situ measurements with high-resolution aerial data presents a promising direction for sustainable forest management in the context of global environmental change.

1. Introduction

Nitrogen is an essential nutrient for plant growth and development, influencing photosynthetic capacity, biomass accumulation and general forest productivity. However, nitrogen deficiency is becoming increasingly common due to anthropogenic impacts, including atmospheric deposition and changes in land use that alter soil nutrient dynamics (Östersund et al., 2024). In Boreal Forests, where weather conditions are usually limiting, nitrogen deficiency can translate into observable physiological stress, finally affecting trees vigor and susceptibility to pests and diseases. Such stress conditions can be quantified through various physiological metrics, but traditional assessment methods are generally very laborious and may not properly capture the spatial heterogeneity inherent in forest ecosystems.

The use of drone imaging to evaluate forest health has gained significant traction in the field of forestry, reflecting a broader change to leverage technological advances in environmental monitoring. Unmanned Air Vehicles (UAVs) equipped with high resolution image sensors provide an effective tool for capturing detailed data on forest conditions, thus improving traditional forest management practices. One of the main advantages of drone imaging provides enhanced data acquisition capabilities. UAV technology facilitates detailed evaluations of forest structures and health indicators, employing a variety of sensors that capture multispectral, hyperspectral and thermal images. These various data sets allow us to investigate forest dynamics with greater granularity than conventional air methods or soil research allows. For example, the comparative spatial resolution provided by drone images reveals health status and vegetation stress that are usually neglected in wider scale evaluations (Fraser and Congalton, 2021, Tan and Shao, 2015). As highlighted in revisions of Dainelli et al. (2021) and Torres et al. (2021), the versatility of drone imaging applications, such as biomass estimation, species identification and invasive species mapping. The use of multispectral drone images facilitates high resolution air data collection that significantly increases the ability to detect subtle changes in vegetation health associated with nitrogen deficiency and other stressors in forests. The multispectral image can capture reflectance data in various wavelengths, allowing to identify variations in chlorophyll content, water stress and other physiological conditions (Drechsel and Forkel, 2024). Kukkonen et al. (2024) observed that the lower NDVI (Normalized Differential Vegetation Index) values correlate with the decrease of nitrogen availability in forest ecosystems, highlighting the essential role of nitrogen in maintaining photosynthetic vigor and the overall vitality of trees.

Understanding the differences in reflectance in trees due to nitrogen deficiency and stress conditions is not only of ecological importance, but also vital to forest management practices that aim to maintain forest health and resilience in the face of ongoing environmental changes. As global environmental challenges persist and intensify, the implementation of innovative monitoring techniques will be crucial in the development of effective strategies for sustainable forest management and conservation. Previous works, such as Östersund et al. (2024), emphasizes that a multifaceted approach that uses remote sensing technology and in situ measurements is vital for effective forest health assessments.

Our goal was to study the possibilities to map health status of spruce (*Picea Abies*) and outline whether areas that have lack of nitrogen or have other health issues could be mapped. We determined three hypotheses for our research: spectral reflectance of individual needles will reveal health differences of the spruce, drone based 3d-mapping can be used to map individual spruce trees, and third multispectral mapping of individual spruce trees in forests will reveal health differences between trees.

This study investigates concepts at a low Technology Readiness Level (TRL), where the primary objective is to assess its initial feasibility rather than to validate it through extensive empirical data. At this early stage of development, the approach relies predominantly on subjective estimates rather than large-scale field measurements or rigorous experimental validation. Such a methodology is appropriate for exploratory research, where the aim is to identify potential value, challenges, and future directions before committing to resource-intensive testing.

2. Material and Methods

We studied spruce dominant forest test site in Savonranta Savonlinna. The test site was about 18 ha having a wide hill in the middle. An RGB-map of the test site (July, 2024) is presented in Figure 1.

Figure 1. Spruce dominant forest site under the study.

2.1 Detecting different trees

First we made a 3D-imaging campaign at Savonranta in April 2023. We used DJI Phantom 4 RTK quadcopter to map the test site with total of 936 photos. This drone provided high resolution RGB imagery. The flying altitude was 60 meters and we collected nadir and tilted images. The orthomosaic and 3D-model were automatically calculated with Dronedeploy-software. During the imaging the soil was partially covered with snow but there was no snow on the trees. This made it easy to detect evergreen trees, namely spruce and pines. Figure 2 shows the orthomosaic result of that campaign.

Figure 2. Orthomosaic from the test site at early Spring.

A screen capture of the 3D-model is shown in Figure 3. Individual trees can be seen as spikes.

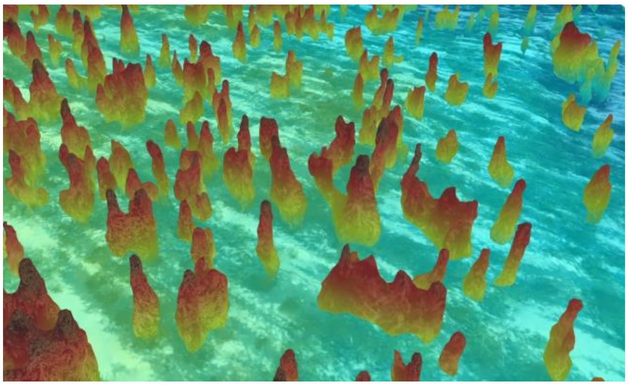

Figure 3. Individual trees on 3D-capture. Spruces can be seen as spikes.

A wider landscape of the 3D-trees are seen in Figure 4.

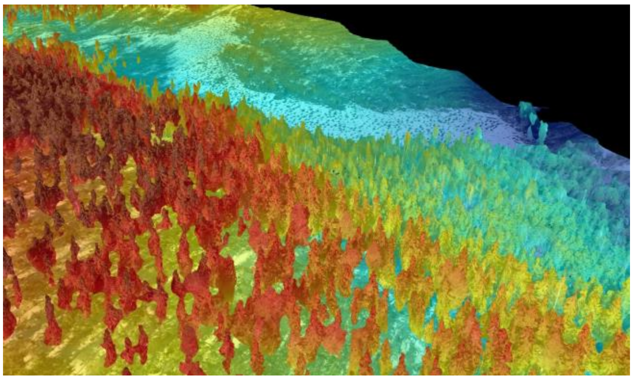

Figure 4. Landscape capture of the 3D-model.

Next, a spatial analysis method called “local max” with Microimages TNT-GIS was delivered. The density parameters were adjusted manually to visually correspond separate trees. Figure 5 shows detected tree tips. This was manually adjusted to identify only spruces with the sharpest treetop at the forest. A swirl or irregular shape of individual trees can be seen also in Figure 5. This was caused by the wind. We did not make any other separation between spruces and pines.

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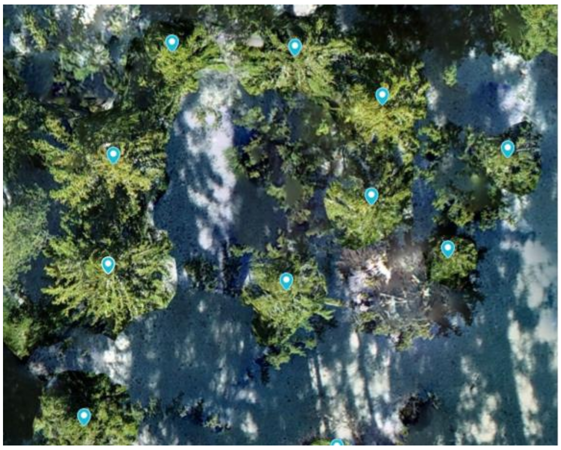

Figure 5. Located spruces from 3D-model.

With this system, we located 3162 individual trees that were assumed to be spruces. After that, we calculated a buffer zone around individual tree spots. We selected the radius to be 80 cm so the circle was about 2 square meters. With this methodology, we wanted to focus on the center of the spruce tree and separate different trees. Circles representing trees are presented in Figure 6.

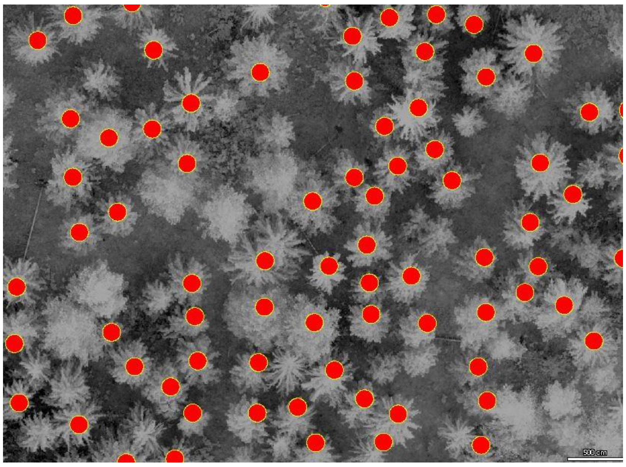

Figure 6. Red dots representing found spruce tips that were analyzed.

All the found trees are presented in the Figure 7. Different test plot borders are also visible in the Figure 7.

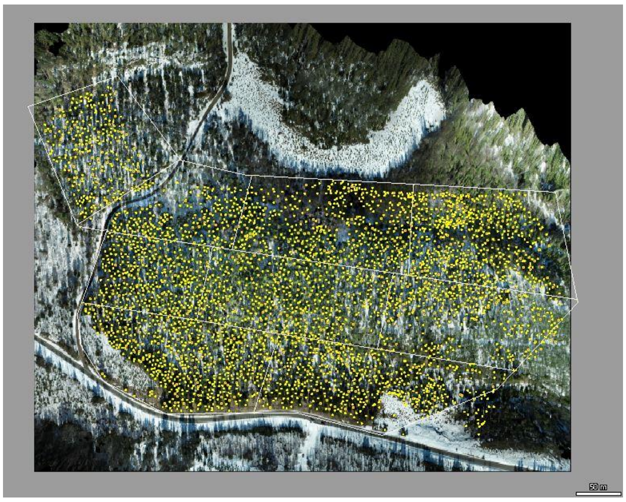

Figure 7. Identified trees on the entire test area. The trees are well distributed around the area.

2.2 Spectral reflectance of individual needles

Next we used a leaf spectrometer CI-710 (CID Bio-Science) to measure reflections of separate needle clusters. The instrument provides measurements from the range of 360 nm to 1100 nm. In each measurement case, we taped 4-5 distinct needles together from the other side. We selected six different spruce trees to measure reflectance monthly around the growing season. The classification of these trees was only based on subjective observation. Two trees were normal, two trees were estimated to have lack of nutrients, and two trees had an external stress source since they lost about 1/3 of their roots. All trees were 10-25 m long. Needle samples were taken from the higher parts of the trees. Selected needles were from previous-year shoots. Two different sample sets of individual trees were measured in each time, and two different needle samples from individual twig was measured. We made each measurement twice. We carried out a total of 288 spectrometer measurements.

We calculated means of our spectrometer results, and calculated average spectral reflectance curves for the three classes: normal, lack of nutrients, general stress from the autumn data. Figure 8 shows the average spectral curve of the needles in normal conditions (July and August) and the subtracted results of spectral curve differences to lack of nutrients and stress.

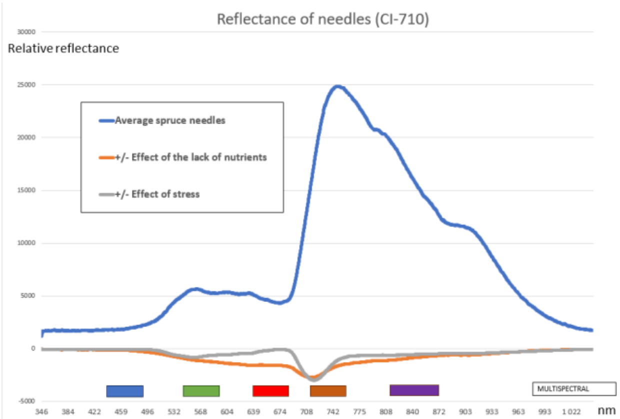

Figure 8. Spectral curves and subtracted curves of spruce needles in different conditions. In addition, wavelengths of used multispectral camera are presented. Subtractions show how much the curve will change if such conditions appear.

	Blue	Green	Red	RE	NIR
Healthy %	8.2	24.9	21.7	100.0	73.3
Nutrient lack %	7.6	24.3	14.7	89.8	69.3
Stress %	7.8	21.4	20.5	89.8	70.7
Wavelength (nm)	450	560	650	730	840
Width (nm)	+-16	+-16	+-16	+-16	+-26

Table 1. Calculated relative reflectances from spectrometer results to multispectral wavelengths.

The spectral measurement results in Figure 8 are averaged to represent multispectral drone wavelengths in Table 1. The impact of nutrient lack should be seen especially in RED wavelength channel.

The multispectral channels of DJI Phantom 4 Multispectral are also presented in Figure 8. This camera has six bands: blue, green, red, red edge, and near infrared. It can be seen from Figure 8, that red and red edge bands are measuring the spectral wavelengths that have lots of differences between the spruces that we measured with handheld leaf spectrometer.

2.3 Multispectral mapping of the test site

After the leaf spectrometer measurements, we carried out a multispectral drone mapping campaign to the test site in Savonranta. We used the DJI Phantom 4 Multispectral quadcopter drone with RTK base station. The flying altitude was about 100 meters. We used Solvi – drone-based analytics for field trial assessments -software to automatically produce multispectral orthomosaics. The RGB representation of part of the orthomosaic is represented in Figure 9. The same location from the Red Edge band is presented in Figure 10. To clarify processing pipelines, high resolution RGB images (DJI Phantom 4 RTK) and Dronedeploy software was used for 3D-model of the forest, and multispectral mapping (DJI Phantom 4 Multispectral) with Solvi software were used to produce multispectral orthomosaics.

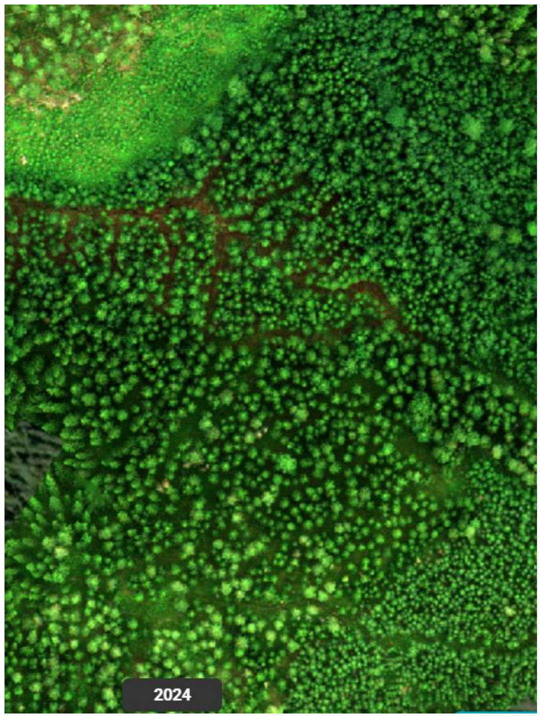

Figure 9. RGB capture of the multispectral orthomosaic.

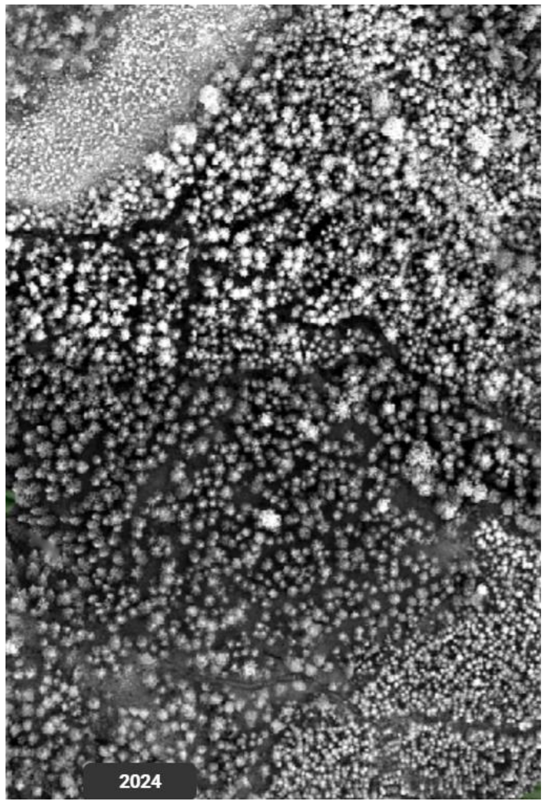

Figure 10. Red Edge data from the same location as Figure 9. emphasizing the areal differences.

Our next goal was to compare spectral reflectance of identified spruces to the other area. For the comparison, we calculated the average values of the entire field by generating 2 square meter sample points in a 5 m grid. After that, we generated No Spruce -samples. These samples were done in way that we first calculated a 5m x 5m grid over the entire test site. Then we removed grids that contained identified spruces. Then from the remaining grids we randomly calculated a single location for a no spruce "tree". These calculations were made with Microimages TNT-GIS. No spruce spots were generated for total of 2553 points. After that we calculated average spectral reflectances of spruce, no spruce and site average based on the multispectral drone data.

3. Results and discussion

The mean values of spectral reflectances of spruce, no spruce samples and average samples are presented in Figure 11.

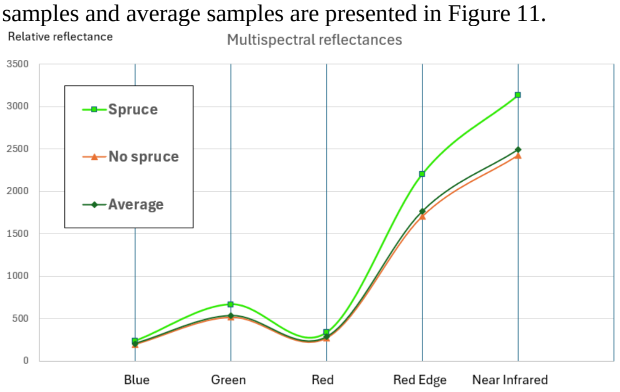

Figure 11. Multispectral Means of spruce (all), no spruce and average. Curves are levelled.

As it can be seen from the Figure 11, the reflectance of spruce spots is higher than the spots of no spruce and average. As expected, the non-spruce areas exhibited the lowest reflectance values. Especially the difference of spruces and other is significant with red edge and near infrared bands, meaning that multispectral technology may reveal health differences.
By focusing on the Red Edge reflectance, the following Figure 12 presents the relative values of reflectance for detected individual spruce trees.

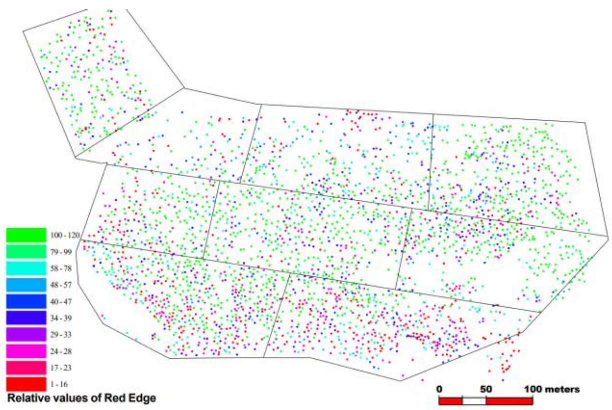

Figure 12. Red Edge reflectance of individual spruces showing the possible local differences.

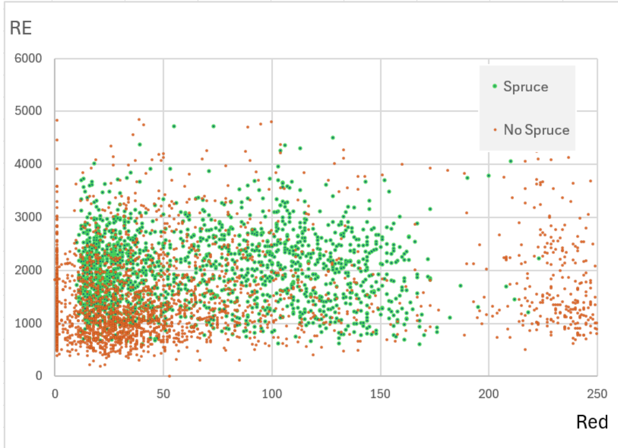

Figure 13. Comparison of Red & RE reflectances of Spruce and No-Spruce categories.

The average RE reflectance of Spruce were 1996 and No Spruce 1469 in Figure 13, which compares the Red and RE reflectances of these classes.

When the reflectance of individual trees are averaged, the following Figure 14 can be represented showing estimated health status of individual spruce trees within different trial plots.

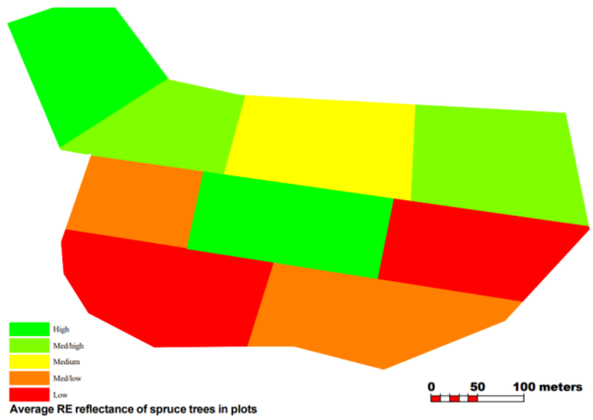

Figure 14. Estimated health status of averaged spruces within trial plots.

As a sample, the following Figure 15 shows the classified spruce trees, and the distribution of generated Non-spruce locations in a same image.

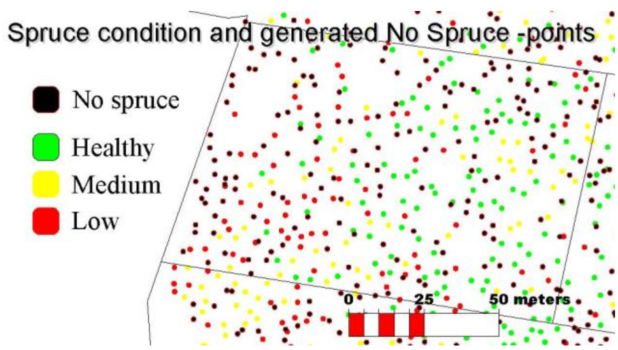

Figure 15. Classified trees and generated trees showing the distribution of points in a single trial plot.

4. Conclusions

Our goal was to study the possibilities to map health status of spruce (*Picea Abies*) and outline that in forest scale. We demonstrated that we can measure separate spruce and estimate differences between their health status.

Our research successfully validated all three proposed hypotheses. First, we demonstrated that the spectral reflectance of individual spruce needles can indicate health differences, with significant spectral differences observed between healthy and stressed specimens. Second, we confirmed that drone-based 3D mapping is an effective method for accurately identifying and mapping individual spruce trees within forest stands. Lastly, our findings showed that multispectral mapping at the individual tree level is capable of detecting spectral variations between trees, enabling fine-scale monitoring of forest health and nitrogen status related issues. Together, these results highlight the potential of integrating spectral analysis and drone-based remote sensing for advanced forest health assessment and management strategies. The following steps for the research would be to combine in-situ data with drone data in order to correlate spectral observations with quantified nitrogen levels and other nutrient status. However, as feasibility study, this work focused on relative differences, it outlines the possibilities how health differences can be determined. In addition, this study shows that separation between different subjective health issues caused by things such as stress or lack of nitrogen are possible to be determined with tree-level multispectral remote sensing. Next steps should focus on comparing the results with field measurements.

Future research should rely on this information by exploring additional environmental stressors that may have an impact on *Picea Abys subp. Abies*, such as the availability of water and the quality of the soil. As demonstrated in the work of Keränen et al. (2024), the evaluation of several scales of trees of trees thanks to combined remote sensing techniques and soil transmission provides a robust framework to treat complex interactions between trees and their environment. The progress of drone technologies and image analysis algorithms are very promising to improve the resolution and precision of spectral measures, allowing more nuanced assessments of trees.

In summary, the research carried out highlights the significant potential of multispectral analysis in forest applications, in particular in the monitoring of nutrient levels and stress conditions. By elucidating the spectral signatures associated with a nitrogen deficiency in *Picea Abies subp. Abies*, we pave the way for future innovations that can improve forest resilience and contribute to global efforts in sustainable forest practices. The continuous exploration of these advanced remote sensing techniques promises to deepen our understanding of forest dynamics and to support the management of these vital ecosystems in the face of current environmental challenges.

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