Mapping Boreal Forest Vitality Using Drone-Based Multispectral Time-Series and Object-Based Classification

Basam Dahy [1], Esra Sengun [1], Johanna Witzell [1], Johan E. S. Fransson [1]

[1] Department of Forestry and Wood Technology, Linnaeus University, Växjö, Sweden – bassam.saeed@lnu.se, esra.sengun@lnu.se, johanna.witzell@lnu.se, johan.fransson@lnu.se

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Abstract

Monitoring tree vitality in boreal forests is increasingly critical under escalating climate stress and pest disturbances. This study presents a novel UAV-based framework integrating multispectral imaging, object-based classification, and in-situ physiological sensing for individual tree health assessment. Implemented at the Svartberget research park in northern Sweden, the approach leverages 15 UAV-acquired time-series image stacks (2024–2025) combined with sap flow, dendrometer, and stem water content and potential measurements across spruce, pine, and birch. Statistical analysis of reflectance profiles revealed strong spectral separation, particularly in the red edge and near-infrared bands, enabling early discrimination of vitality classes. Preliminary findings demonstrate the framework's capacity to detect physiological stress signals and inter-species differences, offering a pathway toward operational forest health monitoring. The method is designed for upscaling to the 2,300 ha Attsjö super test site, where multi-sensor data fusion will support landscape-level implementation. This work highlights the value of UAV–sensor integration for precision forestry and climate-resilient ecosystem management.

1. Introduction

The boreal forest biome, one of the largest continuous forested regions globally, plays a pivotal role in regulating the Earth's carbon cycle and sustaining biodiversity. Monitoring the vitality of dominant tree species such as Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), and birch (*Betula* spp.) is increasingly important in the context of climate-induced stressors, bark beetle outbreaks, and anthropogenic disturbances (Seidl et al., 2017; Hlásny et al., 2021; Huo et al., 2024).

Unmanned Aerial Vehicles (UAVs) equipped with multispectral sensors have become central tools for fine-scale, temporally resolved forest health assessments. By capturing reflectance in key spectral bands, UAVs allow the estimation of vegetation indices, which are sensitive to early signs of physiological stress. When combined with object-based image analysis (OBIA), these data facilitate individual tree-level classification and vitality evaluation across time (Kanerva et al., 2022; Sun et al., 2022; Nasiri et al., 2023; Dersch et al., 2023).

This study presents a UAV-OBIA framework applied at the Svartberget research park in northern Sweden for health monitoring of individual trees and planned to be applied in larger study area at the Attsjö super test site in southern Sweden. The approach integrates UAV-derived spectral time-series with in-situ physiological sensor data, including sap flow, stem water content and potential, and dendrometric growth. This integration bridges the gap between remote spectral observations and tree-level physiological responses, offering a powerful methodology for scalable forest vitality assessment.

2. Materials and Methods

2.1 Study Areas and Monitoring Framework

This study was conducted at the Svartberget research park, situated in the boreal zone of northern Sweden (64.24434°N, 19.76646°E) (Figure 1). Managed by the Swedish University of Agricultural Sciences (SLU), Svartberget is a long-term research facility that supports interdisciplinary investigations in forest ecology, hydrology, and environmental monitoring. The landscape consists primarily of coniferous forests, dominated by *Picea abies* (Norway spruce) and *Pinus sylvestris* (Scots pine), with scattered stands of *Betula* spp. (birch). Given its history of bark beetle infestations and climatic sensitivity, Svartberget provides an ideal setting for assessing the spectral and physiological dynamics of tree vitality.

Future expansion of the methodology is planned at the Attsjö super test site in southern Sweden (56°53'07.5"N, 15°08'00.4"E). This 2,300-hectare site integrates UAV (RGB, multispectral, and LiDAR sensors) observations and AI-based data platforms, offering an ideal opportunity for scaling up fine-resolution forest monitoring across diverse boreal forest environments.

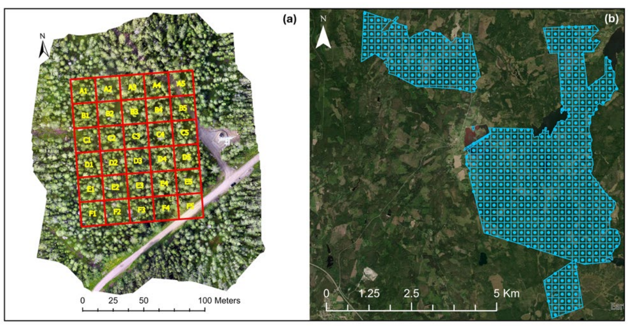


Figure 1. Overview of study areas. Left: Svartberget research park (1 ha), where UAV multispectral time-series (2024–2025) and physiological sensors enable tree-level vitality monitoring. Right: Attsjö super test site (2,300 ha) with UAV RGB, multispectral, and LiDAR data for forest monitoring upscaling.

2.2 UAV Platform and Flight Configuration

Multispectral data were acquired using the DJI Mavic 3 Multispectral (M3M). The M3M is equipped with RGB camera plus four monochromatic bands, green (560 ± 16 nm), red (650 ± 16 nm), red edge (730 ± 16 nm), and near-infrared (860 ± 26 nm), that enable the derivation of vegetation indices sensitive to chlorophyll content, stress detection, and canopy structure.

Flights were conducted using an "Area Route" protocol with optimized elevation parameters. Each mission was flown at 80 meters above ground level, yielding a high-resolution ground sampling distance (GSD) of 3.69 cm/pixel. Lateral and frontal overlaps were configured at 80% and 90%, respectively, to ensure redundancy for 3D reconstruction and spectral calibration (Table 1).

Missions were planned to capture phenological transitions and maximize comparability across the vegetation season (2024 and 2025). The UAV returned to the take-off point upon completion of each flight, and all settings were standardized to ensure data consistency.

Item	Description
Platform	DJI Mavic 3 Multispectral
Sensor	Integrated Multispectral Camera (RGB + Green, Red, Red Edge, NIR)
Flight Dates	15 flights: 2024 (full vegetation season) + 2025 (April, May, and June)
Altitude (AGL)	From 62.54 m to 69.39 m, optimized for canopy clearance and res.
GSD	1.83 cm/pixel to 2.04 cm/pixel, enabling single-tree analysis
Area Covered	3.19 ha to 3.49 ha per flight, focused on a 1-ha core plot
Images Count	182 images per flight, ensuring consistent spatial coverage
AT RMS Error	0.94 pixel to 1.18 pixel, indicating high geometric alignment accuracy
Geo RMSE	0.02 m to 0.12 m, precise RTK positioning for temporal analysis
TDOM Resolution	1.91 cm/pixel to 2.17 cm/pixel, supporting fine-scale mapping
Overlap (side/front)	80% / 90%

Flight Dates = When the flights took place.
Timeline = The broader campaign timeframe.
Altitude (AGL) = Average flight altitude above ground level.
GSD = Ground Sampling Distance.
Area Covered = Mapping coverage per mission in hectares.
Image Count = Total number of photos per flight.
AT RMS Error = Aerotriangulation Root Mean Square error (geometric alignment quality).
Geo RMSE = Georeferencing Root Mean Square Error, showing spatial accuracy.
TDOM GSD = Ground Sampling Distance of the True Orthophoto Mosaic.

Table 1. Summary of UAV flight specifications.

2.3 Flight Campaigns and Image Processing

A total of ten UAV missions were conducted between April and November 2024, covering the full phenological cycle from pre-leaf-out to late senescence. Five additional flights from the early season (April–June 2025) complemented the ten previously conducted in 2024. Each flight was performed under stable conditions, with careful monitoring of solar angle and cloud cover (Table 2). These time points were selected to enable both intra- and inter-species comparison under dynamic phenological conditions. The late spring flights were particularly important for capturing early divergence between healthy and declining individuals, as supported in Junttila et al. (2022).

Post-flight image processing was conducted using DJI Terra software, configured for standalone high-resolution orthomosaic generation. Radiometric corrections and reflectance normalizations were applied to each multispectral band using internal camera calibration and flight metadata.

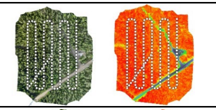
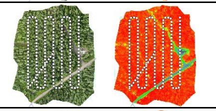
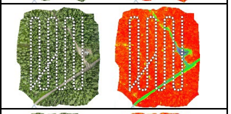
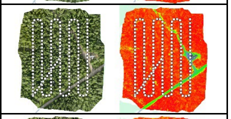
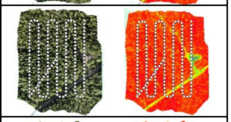
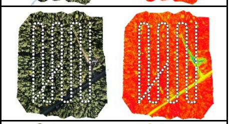
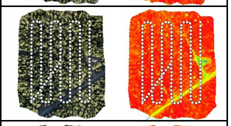
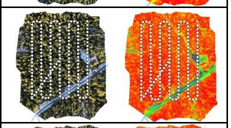
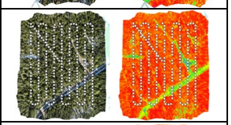
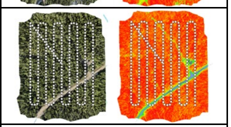
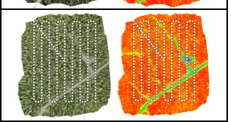
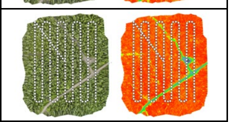
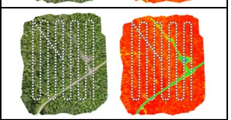
Date	Time	Solar Angle	Cloud Cover	Snapshot (RGB/NDVI)
31.05.2024	15:48	39.3°	Cloudy	
08.07.2024	14:50	42.7°	Cloudy	
20.07.2024	11:35	44.4°	Sunny	
04.08.2024	11:55	42.2°	Cloudy	
17.08.2024	12:31	38.9°	Sunny	
29.08.2024	13:09	34.8°	Sunny	
14.09.2024	12:38	28.9°	Sunny	
28.09.2024	11:09	21.4	Sunny	
12.10.2024	11:24	17.4°	Sunny	
11.11.2024	12:53	8.5°	Cloudy	
26.04.2025	11:07	32.5°	Sunny	
18.05.2025	14:37	44.0°	Sunny	
30.05.2025	11:26	46.0°	Cloudy	
12.06.2025	10:50	53.0°	Cloudy	
29.06.2025	13:03	60.0°	Cloudy	

Table 2. Time-series snapshots of UAV-acquired RGB imagery and derived NDVI composites from Svartberget research park (Sweden), captured during the 2024 and 2025 vegetation seasons.

2.4 Tree Selection and Ground Sensor Deployment

A total of 76 trees were selected for individual-level monitoring, including 60 dead trees and 16 live trees (Figure 2). The selection spanned the three dominant species: spruce, pine, and birch. The live trees were categorized based on their sensor instrumentation: (a) eight trees (4 spruce, 4 pine) were equipped with advanced sap flow and water content and potential sensors installed at three vertical heights (1.3 m, 8 m, and 15 m) (Table 3), and (b) the remaining eight trees (4 pine, 3 spruce, 1 birch) were equipped with high-resolution dendrometers for monitoring stem diameter dynamics. This tree-level integration of spectral and physiological data represents a novel approach in remote sensing-based forest vitality assessment and aligns with emerging best practices in eco-physiological monitoring.

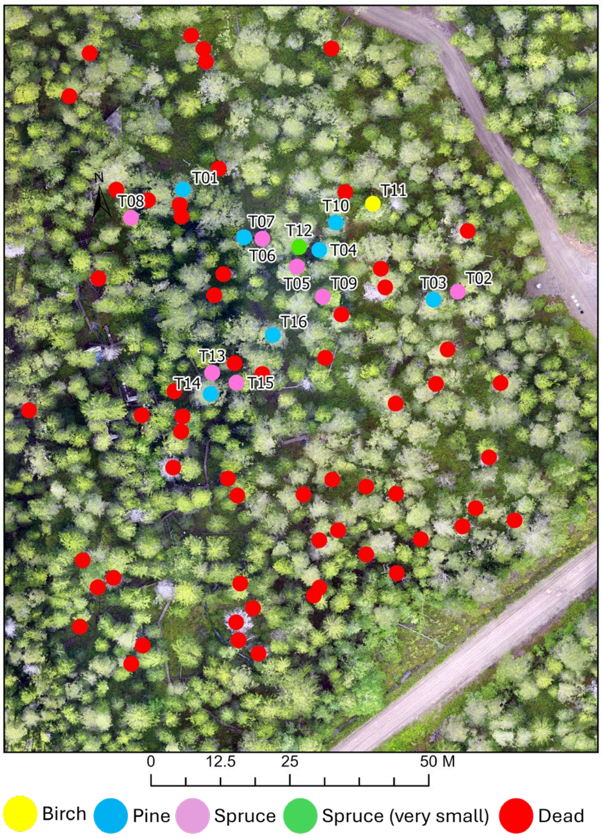


Figure 2. Spatial distribution of the 16 instrumented live trees and 60 dead trees within the Svartberget pilot site. Symbols represent species (pine, spruce, birch) and correspond also to sensor configurations (sap flow, dendrometer, water potential) as indicated in Table 3.

2.5 Object-Based Classification

Object-based image analysis (OBIA) was conducted using the Objective tool in ERDAS IMAGINE 2024. Multispectral orthomosaics served as inputs for multi-resolution segmentation, optimized for crown-level delineation within the 1-ha area size. Classification rules were built using spectral, textural, and geometric attributes. A supervised Random Forest classifier was trained on field-verified crown objects representing spruce, pine, birch, and dead trees. Post-processing included removal of shadow artifacts and correction of small misclassified objects.

The resulting crown polygons were exported as vector layers with class attributes and time-series index values, enabling detailed analyses of species and vitality dynamics over time.

Tree ID	Species	Sensor Type	Heights (m)
T01	Pine	SapFlow + FloraPulse + TEROS	1.3, 8, 15
T02	Spruce	SapFlow + FloraPulse + TEROS	1.3, 8, 15
T03	Pine	SapFlow + FloraPulse + TEROS	1.3, 8, 15
T04	Pine	SapFlow + FloraPulse + TEROS	1.3, 8, 15
T05	Spruce	SapFlow + FloraPulse + TEROS	1.3, 8, 15
T06	Spruce	SapFlow + FloraPulse + TEROS	1.3, 8, 15
T07	Pine	SapFlow + FloraPulse + TEROS	1.3, 8, 15
T08	Spruce	SapFlow + FloraPulse + TEROS	1.3, 8, 15
T09	Spruce	Dendrometer	1.3
T10	Pine	Dendrometer	1.3
T11	Birch	Dendrometer	1.3
T12	Spruce (V.S.)	Dendrometer	1.3
T13	Spruce	Dendrometer	1.3
T14	Pine	Dendrometer	1.3
T15	Spruce	Dendrometer	1.3
T16	Pine	Dendrometer	1.3

Table 3. Summary of instrumented tree species and sensor types.

2.6 Spectral Profile Extraction and Time-Series Analysis

Multitemporal spectral profiles were extracted for the selected trees to characterize seasonal reflectance patterns and assess inter-species differences in vitality. Fifteen UAV-acquired datasets (2024–2025) were preprocessed and stacked into temporal image cubes for each spectral band (RGB, green, red, red-edge, NIR). For each of the 16 live trees and 60 dead trees, a 0.5 m radius buffer was applied to crown centers. Within these buffers, mean digital numbers were extracted across all layers. The profiles were then aggregated by species (spruce, pine, birch) and health status (live vs. dead) to assess temporal trends and spectral divergence. This analysis provides a robust foundation for detecting early signs of stress, species-specific phenological patterns, and supporting future machine learning applications. It directly informs the results presented in the following section, including time-series comparisons across tree types and health classes.

2.7 Integration of UAV and Ground-Based Sensors

To enhance the interpretation of UAV-derived reflectance data, sixteen live trees were instrumented with ground-based physiological sensors. Eight trees (four spruce and four pine) were equipped with sap flow and water content and potential sensors, installed at three vertical levels (1.3 m, 8 m, and 15 m) to capture within-tree variation. The remaining eight trees (including birch, spruce, and pine) were fitted with dendrometers to measure stem diameter changes over time. These sensors offer real-time insights into transpiration, water availability, and growth, providing critical context for interpreting temporal changes in spectral signatures. By synchronizing physiological measurements with UAV image acquisition dates, this hybrid approach enables a more holistic understanding of tree vitality dynamics.

2.8 Scaling Potential and Future Integration

The integrated monitoring framework developed at Svartberget is designed for upscaling to the 2,300 ha Attsjö super test site (Figure 3). Attsjö's advanced infrastructure, including UAV optical and LiDAR data provides an ideal environment for expanding tree-level vitality monitoring to landscape scales. By combining multispectral imaging, OBIA, and physiological sensors, the framework enables scalable, multimodal assessment of forest health across boreal systems.

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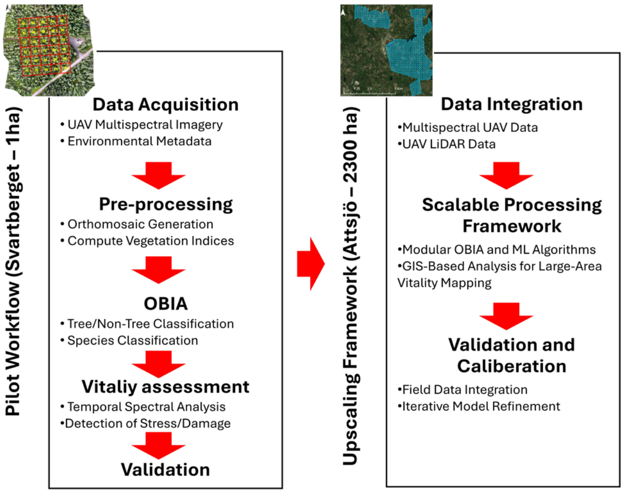

Figure 3. Workflow for UAV-based boreal forest vitality mapping at Svartberget research park (pilot study, 1 ha) and framework for upscaling to the Attsjö super test site (2,300 ha).

3. Results

Preliminary Spectral Trends Among Tree Vitality

UAV multispectral imagery acquired across 15 dates from the 2024 and 2025 vegetation seasons revealed consistent and interpretable patterns in canopy reflectance for different tree vitality classes. Average digital number (DN) values were extracted from five spectral bands (RGB, green, red, red edge, and NIR) for 16 live trees and 60 dead trees, categorized as spruce, pine, birch, and dead (Figure 4).

Live conifers (spruce and pine) exhibited higher reflectance in the red edge and NIR bands, especially during summer (June–October), reflecting healthy canopy structure and high chlorophyll content. Notably, pine crowns showed the highest overall NIR response, peaking at 1,495 on 28 September 2024, while spruce reached 1,400 on 12 October 2024. **Dead trees** showed consistently lower reflectance across all bands, with little seasonal variation. Their red edge and NIR values remained below 520 throughout the time series, sharply contrasting with the higher, dynamic profiles of live conifers. These spectral patterns reflect canopy desiccation and pigment loss. **Birch**, although represented by a single individual, displayed greater variability, particularly in the red edge and green bands. Its reflectance was lower than spruce and pine in NIR, and in some cases, close to dead trees in visible bands. This may reflect both species-level traits and individual stress response. **Seasonal patterns** were evident across all bands. In spring (April–May 2025), lower values were observed in the green and red bands, gradually increasing into peak summer. Differences between healthy and dead trees became more distinct after late May, particularly in red and red edge bands. RGB signals remained relatively stable and were less effective in capturing physiological stress, highlighting the added value of narrowband multispectral data.

These preliminary results demonstrate that multispectral UAV data can effectively differentiate tree vitality classes, with red edge and NIR bands showing the strongest potential for distinguishing live and dead crowns. The distinct temporal signatures observed for spruce, pine, and dead trees support the use of time-series spectral analysis in high-resolution forest health monitoring frameworks.

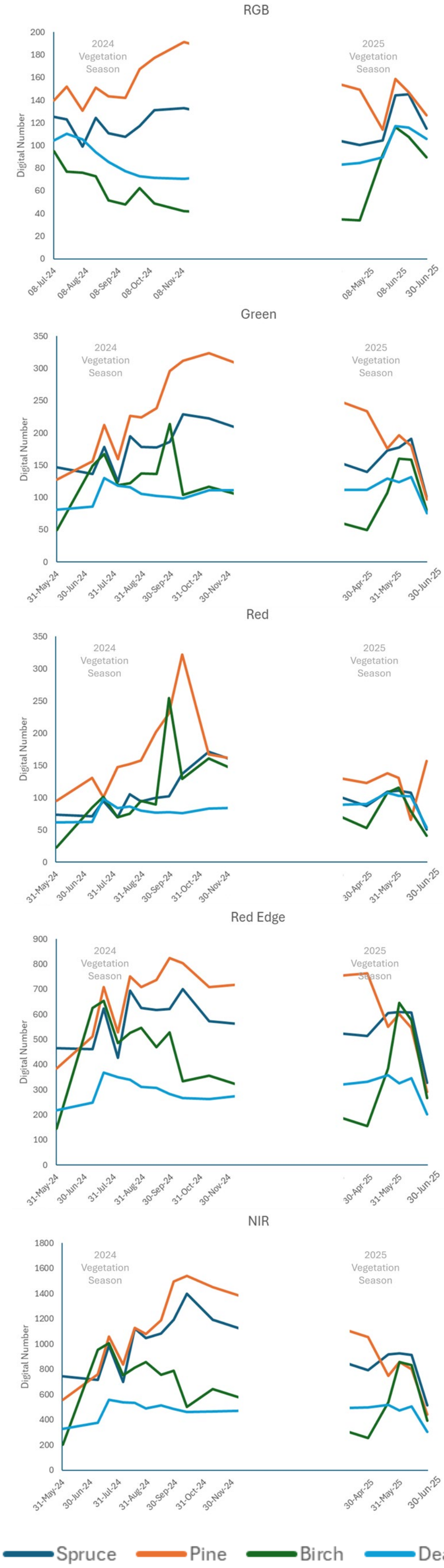

Figure 4. Mean spectral profiles (DN) of spruce, pine, birch, and dead trees across five bands from 15 UAV flights (2024–2025).

4. Discussion

This study demonstrates the feasibility of deploying a UAV-based multispectral framework for monitoring individual tree vitality in boreal forests. The time-series reflectance analysis (Section 3) provided robust differentiation of spruce, pine, and dead trees, highlighting the diagnostic power of red edge and NIR bands for detecting canopy health.

Although we did not include all OBIA outputs in this conference submission, the underlying workflow, crown segmentation via ERDAS Objective followed by object-level classification, follows best practices in high-resolution image processing. OBIA enhances accuracy and interpretability by leveraging spectral, spatial, and textural information at the object scale. In urban environments, OBIA has demonstrated improved classification consistency compared to pixel-based approaches; our deployment in forested settings aligns with these findings (Ecke et al., 2022). A comprehensive assessment of crown delineation, shadow mitigation, and class-specific accuracy is in progress and will be presented at the full paper stage.

While full integration of sap flow, water content and potential, and dendrometer data remains ongoing, this physiological layer is crucial for linking spectral signals to tree water balance and stress response (Budianti et al., 2022). UAV-derived phenological metrics have shown predictive value for sap flow in temperate forests, supporting our approach of aligning biophysical measurements with remote observations. Once completed, similar correlations will strengthen the framework's ecophysiological validity.

By combining temporal UAV imagery with OBIA and physiological sensors, this pilot establishes a scalable model for dynamic forest monitoring. As outlined, the methodology supports transferability to larger sites like Attsjö, where it can integrate UAV optical and LiDAR imaging. This synergy addresses recognized limitations in current UAV-based forest health monitoring, especially the need for long-term multisensor workflows and standardized analysis pipelines.

5. Conclusion and Future Works

This pilot study presents an integrated UAV-OBIA-sensor framework for detailed monitoring of individual tree vitality in boreal forests. Key outcomes include:

- Demonstrated capacity of spectral time series (especially red edge and NIR) to differentiate species and detect physiological stress.
- Implementation of high-resolution OBIA classification with robust seasonal tracking of 76 trees.
- Synchronization of UAV and in-situ physiological measurements to enhance interpretation and ground validation.

The Svartberget research park served as a successful testbed for refining the framework, which is now being scaled to a larger, technologically advanced landscape at the Attsjö super test site.

Several directions will guide the next phase of this research:

1. **Integration of Indices:** All 15 image stacks (along with the additional images to be acquired by drone flights through the end of the 2025 vegetation season, as planned) will be processed to generate time-series vegetation indices (e.g., NDVI, NDRE, OSAVI, GNDVI, LCI), which will be statistically compared across tree classes to identify the most sensitive indicators.

2. **Physiological-Spectral Modelling:** Once sensor datasets are fully quality-checked, regression models and machine learning (e.g., random forest, support vector machines) will be applied to link physiological metrics to spectral responses.

3. **Scaling to Attsjö:** The full monitoring workflow, including object segmentation, spectral extraction, and classification, will be adapted and applied over the 2,300 ha Attsjö site using optical and LiDAR-enhanced canopy models and AI tools.

4. **Data Fusion:** Integration with Sentinel-2 and Landsat-9 or other satellite imagery will be explored for upscaling and continuity during UAV data gaps.

5. **Tool Development:** As part of long-term project goals, outputs will be incorporated into user-friendly geospatial applications for forest health management and early warning systems.

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References

Budianti, N., Naramoto, M., Iio, A., 2022: Drone-sensed and sap flux-derived leaf phenology in a cool temperate deciduous forest: a tree-level comparison of 17 species. *Remote Sens.*, 14(10), 2505. doi.org/10.3390/rs14102505.

Dersch, S., Schoettl, A., Krzystek, P., Heurich, M., 2023: Towards complete tree crown delineation by instance segmentation with Mask R–CNN and DETR using UAV-based multispectral imagery and LiDAR data. *ISPRS Open J. Photogramm. Remote Sens.*, 8, 100037. doi.org/10.1016/j.ophoto.2023.100037.

Ecke, S., Dempewolf, J., Frey, J., Schwaller, A., Endres, E., Klemmt, H.-J., Tiede, D., Seifert, T., 2022: UAV-based forest health monitoring: A systematic review. *Remote Sens.*, 14(13), 3205. doi.org/10.3390/rs14133205.

Hlásny, T., König, L., Krokene, P., Lindner, M., Montagné-Huck, C., Müller, J., Qin, H., et al., 2021: Bark beetle outbreaks in Europe: state of knowledge and ways forward for management. *Curr. For. Rep.*, 7, 138–165. doi.org/10.1007/s40725-021-00142-x.

Huo, L., Koivumäki, N., Oliveira, R.A., Hakala, T., Markelin, L., Näsi, R., Suomalainen, J., et al., 2024: Bark beetle pre-emergence detection using multi-temporal hyperspectral drone images: Green shoulder indices can indicate subtle tree vitality decline. *ISPRS J. Photogramm. Remote Sens.*, 216, 200–216. doi.org/10.1016/j.isprsjprs.2024.07.027.

Junttila, S., Näsi, R., Koivumäki, N., Imangholiloo, M., Saarinen, N., Raisio, J., Holopainen, M., et al., 2022: Multispectral imagery provides benefits for mapping spruce tree decline due to bark beetle infestation when acquired late in the season. *Remote Sens.*, 14(4), 909. doi.org/10.3390/rs14040909.

Kanerva, H., Honkavaara, E., Näsi, R., Hakala, T., Junttila, S., Karila, K., Koivumäki, N., et al., 2022: Estimating tree health decline caused by *Ips typographus* L. from UAS RGB images using a deep one-stage object detection neural network. *Remote Sens.*, 14(24), 6257. doi.org/10.3390/rs14246257.

Nasiri, V., Hawryło, P., Janiec, P., Socha, J., 2023: Comparing object-based and pixel-based machine learning models for tree-cutting detection with PlanetScope satellite images: Exploring model generalization. *Int. J. Appl. Earth Obs. Geoinf.*, 125, 103555. doi.org/10.1016/j.jag.2023.103555.

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., et al., 2017: Forest disturbances under climate change. *Nat. Clim. Change*, 7(6), 395–402. doi.org/10.1038/nclimate3303.

Sun, X., Wang, P., Yan, Z., Xu, F., Wang, R., Diao, W., Fu, K., et al., 2022: FAIR1M: A benchmark dataset for fine-grained object recognition in high-resolution remote sensing imagery. *ISPRS J. Photogramm. Remote Sens.*, 184, 116–130. doi.org/10.1016/j.isprsjprs.2021.12.004.