CHARLES UNIVERSITY
Faculty of Science

Team of Image and Laboratory Spectroscopy

Monitoring Early Stages of Forest Damage Using Time Series of UAV Multispectral and Hyperspectral Data: A Case Study of Bark Beetle Infestation

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Eurosite

Vegetation damage – causes and impact

Key drivers of vegetation damage

- **Abiotic factors** – drought, heatwaves, frost, windthrow, storms, wildfires, air pollution
- **Biotic factors** – insect outbreaks (e.g., bark beetles), fungal pathogens, invasive plant species
- **Anthropogenic drivers** – logging, land-use change, urban expansion, agriculture intensification, infrastructure development, tourism pressure
- **Climate change** – amplifies abiotic and biotic stresses, increases frequency and severity of extreme events

Ecological consequences / impacts

- Loss of biodiversity
- Reduced carbon sequestration & increased emissions
- Altered water cycle & soil degradation
- Landscape fragmentation & invasive species spread
- Decline in ecosystem services & resilience
- Socio-economic losses (forestry, agriculture, tourism, higher management costs)
- Climate feedbacks (warming, floods, fires, landslides

Vegetation damage – principles of remote sensing detection

Vegetation spectral reflectance properties

Visible region (400–700 nm)

Blue (~450 nm) & Red (~670 nm): strong absorption by chlorophyll → green appearance of leaves

Green (~550 nm): weak absorption → higher reflectance, hence the "green" color

Red edge (680–750 nm)

Sharp increase in reflectance between red and NIR

Very sensitive to stress – shifts in the red edge often signal reduced chlorophyll or early stress

Near-infrared (NIR, 750–1,300 nm)

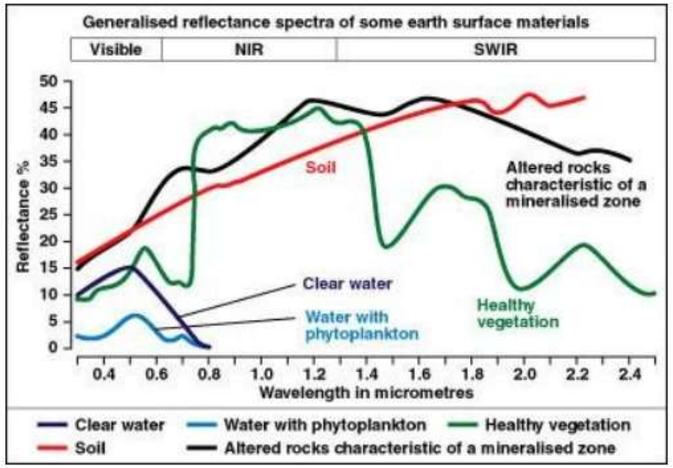
High reflectance due to internal leaf structure (cell walls, air spaces)

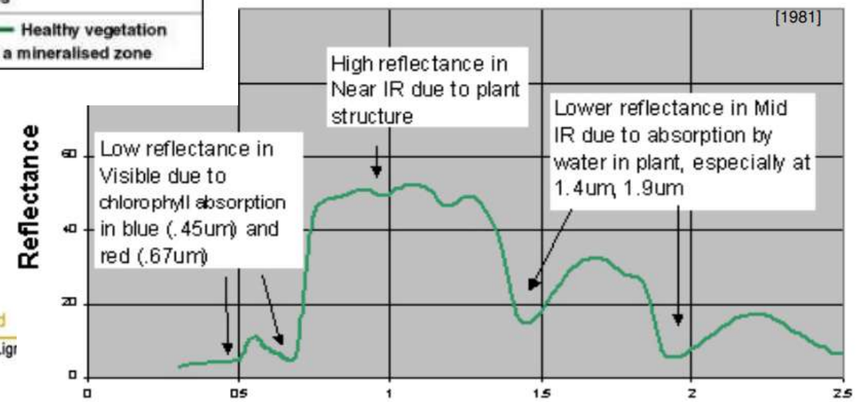
Structural damage or water loss → reduced NIR reflectance

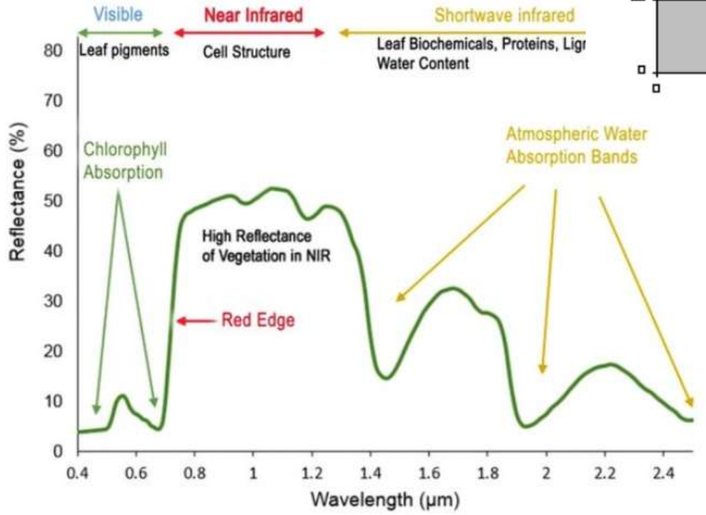
Shortwave infrared (SWIR, 1,300–2,500 nm)

Strong absorption by water, proteins, and lignin

Useful for detecting water stress and tissue degradation





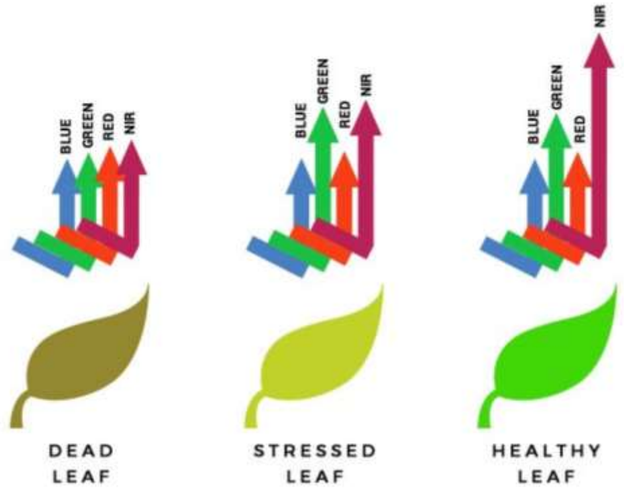


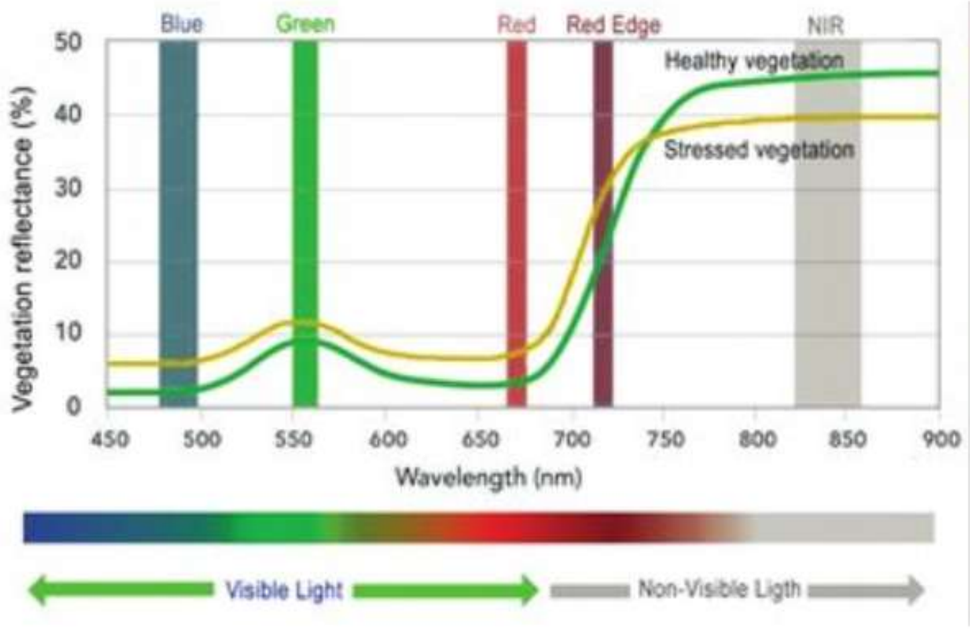
Vegetation damage – features of stressed vegetation

Healthy vegetation: absorption in blue/red, high NIR reflectance

Damaged vegetation: reduced NIR, red edge shift, ↑ visible reflectance

Reduced chlorophyll absorption → higher reflectance in the red band (leaf yellowing/chlorosis)
Flattened red edge → shift toward shorter wavelengths (loss of photosynthetic efficiency)
Lower NIR reflectance → damaged cell structure, reduced leaf turgor
Altered SWIR response → reduced water content, tissue degradation





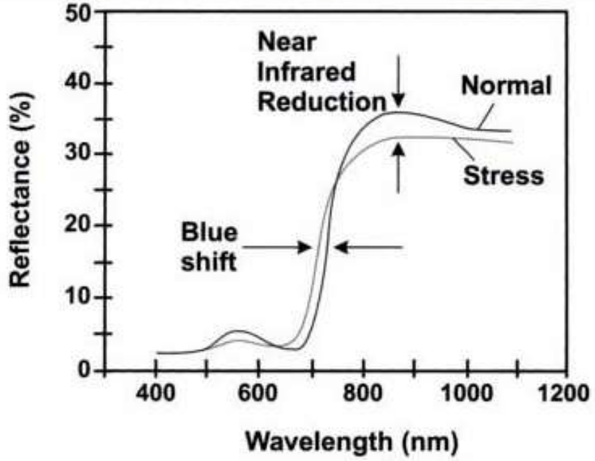
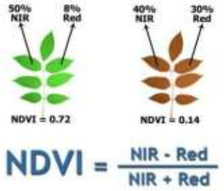
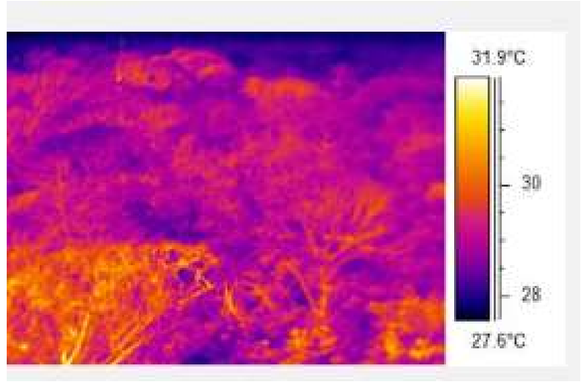


FIGURE 8.6 Spectral response curve shows the expected changes in green leaves under stress. A small reduction in green light reflectance, an increase in red light reflectance, and a reduction in near-infrared light reflectance has been observed. The shift of the red-edge of leaf reflectance to shorter wavelengths, called the blue shift, is a universal property of leaves under stress. (From Reid, N. J. 1987. *Environ. Sci. Technol.*, 21: 428–429. With permission.)

Remote sensing indicators of vegetation damage

Index-based indicators
Decline in NDVI → lower “greenness” due to stress or mortality
Reduced NDRE (red edge index) → early chlorophyll decline
PRI (Photochemical Reflectance Index) changes → altered photosynthetic efficiency
Red edge shift toward shorter wavelengths
Increased reflectance in visible bands (yellowing, chlorosis)





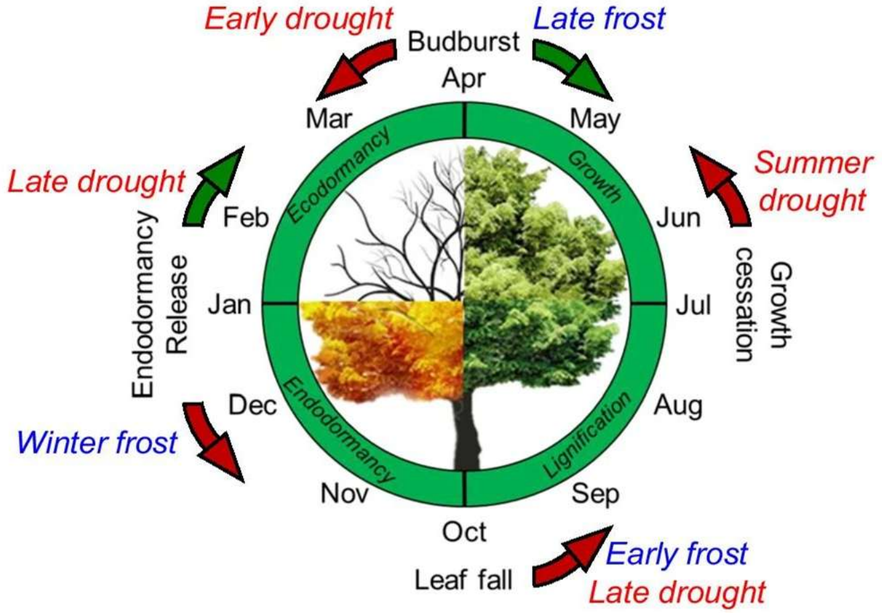
Thermal features
Increased canopy temperature (reduced transpiration, stomatal closure under drought stress).

Structural features
Crown thinning and canopy gaps (LiDAR, UAV photogrammetry).
Radar/SAR backscatter changes → altered canopy roughness and moisture

Temporal features
Delayed or shortened phenological phases (e.g., earlier leaf senescence, reduced spring greening).
Time-series anomalies compared to expected seasonal patterns

Detection of the early damage… challenges: non-specificity, subtle spectral changes, scale dependence, noise, validation difficulty

Physiological vs. structural response – early stress first affects **pigments, water content, and fluorescence signals**, long before visible symptoms or canopy structure changes occur… **possible to detect by remote sensing**



Hastening (brown arrow) or delaying (green arrow) phenological stages in response to drought and frost events. At the center is presented the typical seasonal phenological stages in a deciduous tree in the Northern Hemisphere and outside the potential effects of drought and frost stress depending on their timing. It should be noted that stress factors can have a lagged effect onto phenology (e.g., late drought in the late summer delaying winter dormancy release). Early and late drought typically happen in May–June and September, respectively. Early and late frost typically happen in September–October and April–May, respectively

Charrier, G., Martin-StPaul, N., Damesin, C. *et al.* Interaction of drought and frost in tree ecophysiology: rethinking the timing of risks. *Annals of Forest Science* **78**, 40 (2021). https://doi.org/10.1007/s13595-021-01052-5

Vegetation stress detection using remote sensing – methods

Retrieval methods
- Indices (NDVI, NDRE, PRI)
- RTM (PROSAIL, DART)
- ML/AI
- Trait retrieval

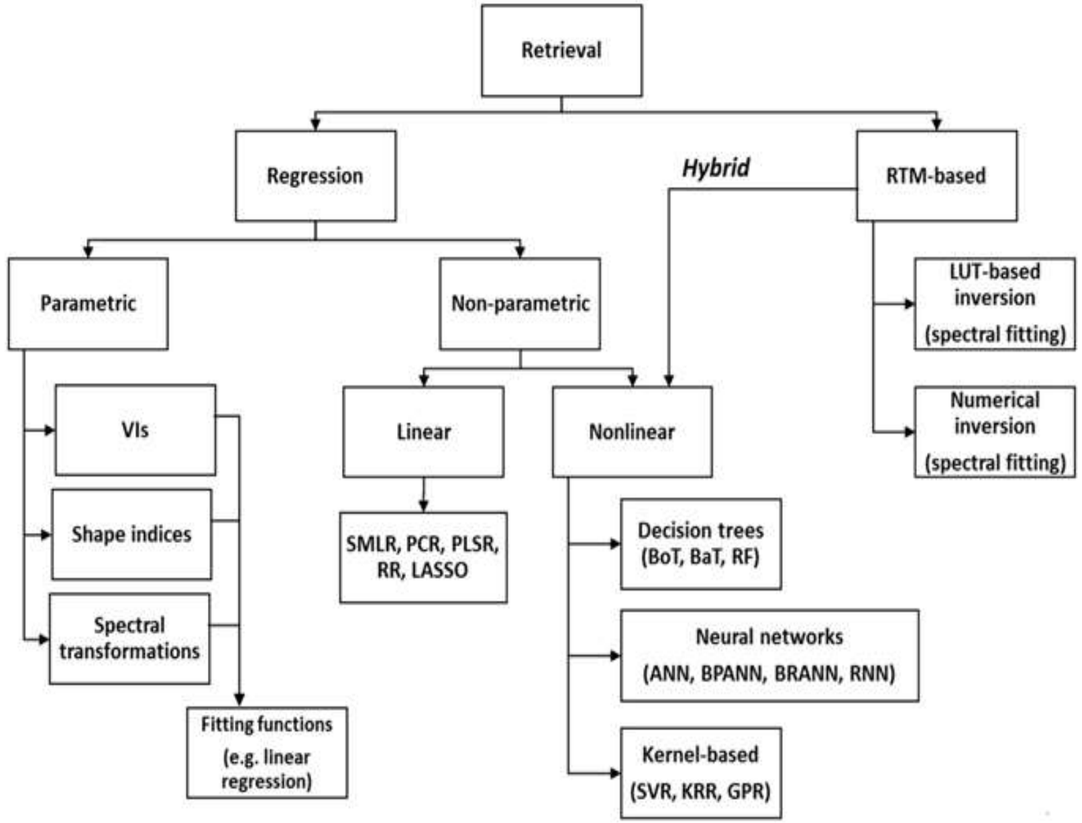
Complementary methods
- Thermal (TIR)
- SAR
- LiDAR

Vegetation Stress Detection

Temporal & change methods
- Time-series
- Phenology
- Change detection
- Trend analysis

Integrated approaches
- Data fusion
- Early warning
- Field validation

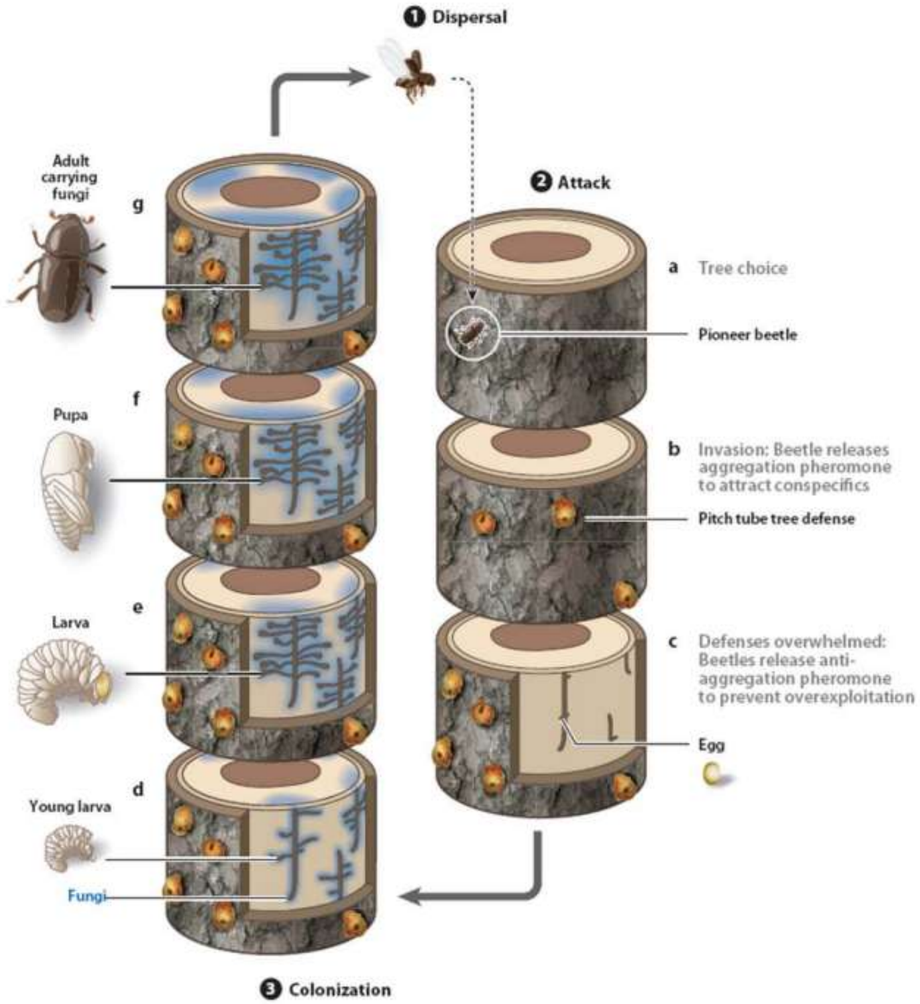
Vegetation damage retrieval methods



Earth Observation Summer School, ESA – Esrin, 2018, Jochem Verrelst: Monitoring and Modelling of Land Surface Processes

EARLY DETECTION OF FOREST DAMAGE CAUSED BY BARK BEETLE

Phases of bark beetle infestation and symptoms of the tree dieback



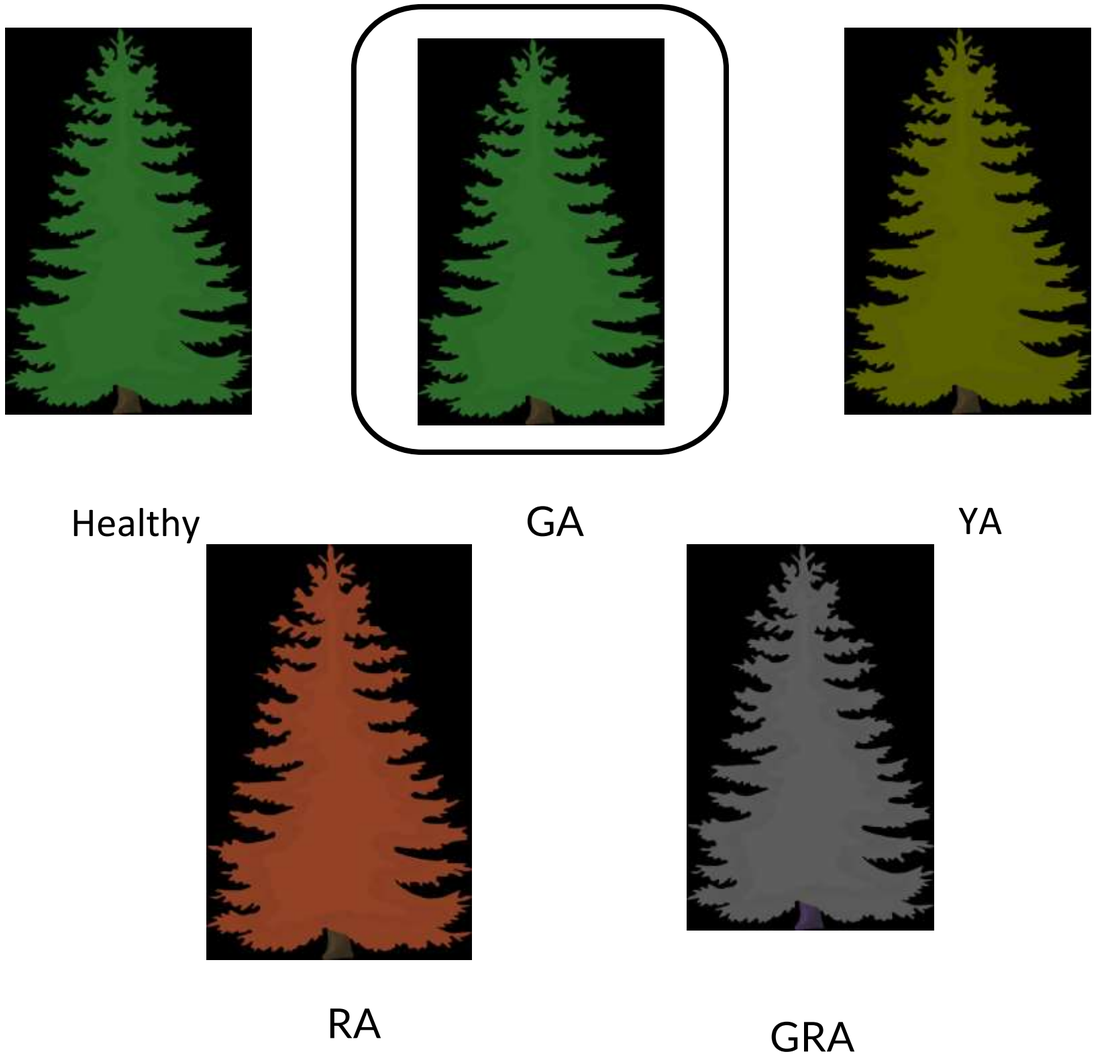
Six, Diana L., and Michael J. Wingfield. 2011. "The Role of Phytopathogenicity in Bark Beetle-Fungus Symbioses: A Challenge to the Classic Paradigm." Annual Review of Entomology 56(January 2011):255–72. doi: 10.1146/annurev-ento-120709-144839.

Healthy GA YA

RA

GRA

EARLY DETECTION OF FOREST DAMAGE CAUSED BY BARK BEETLE



Six, Diana L., and Michael J. Wingfield. 2011. "The Role of Phytopathogenicity in Bark Beetle-Fungus Symbioses: A Challenge to the Classic Paradigm." Annual Review of Entomology 56(January 2011):255–72. doi: 10.1146/annurev-ento-120709-144839.

RESEARCH QUESTIONS

- Can multitemporal UAV hyperspectral and multispectral images detect GAS?
- At what time and within which spectral region can the GAS be first detected?
- Is ground truth data complementary or necessary for GAS detectability?
- What statistical methods are capable of detecting GAS?
- What are the key milestones in the progression of a bark beetle infestation during the green stage that remote sensing should be able to detect in order to enhance bark beetle management?
- **Is remote-sensing detection during the green stage always early enough to be useful??**

Data collection

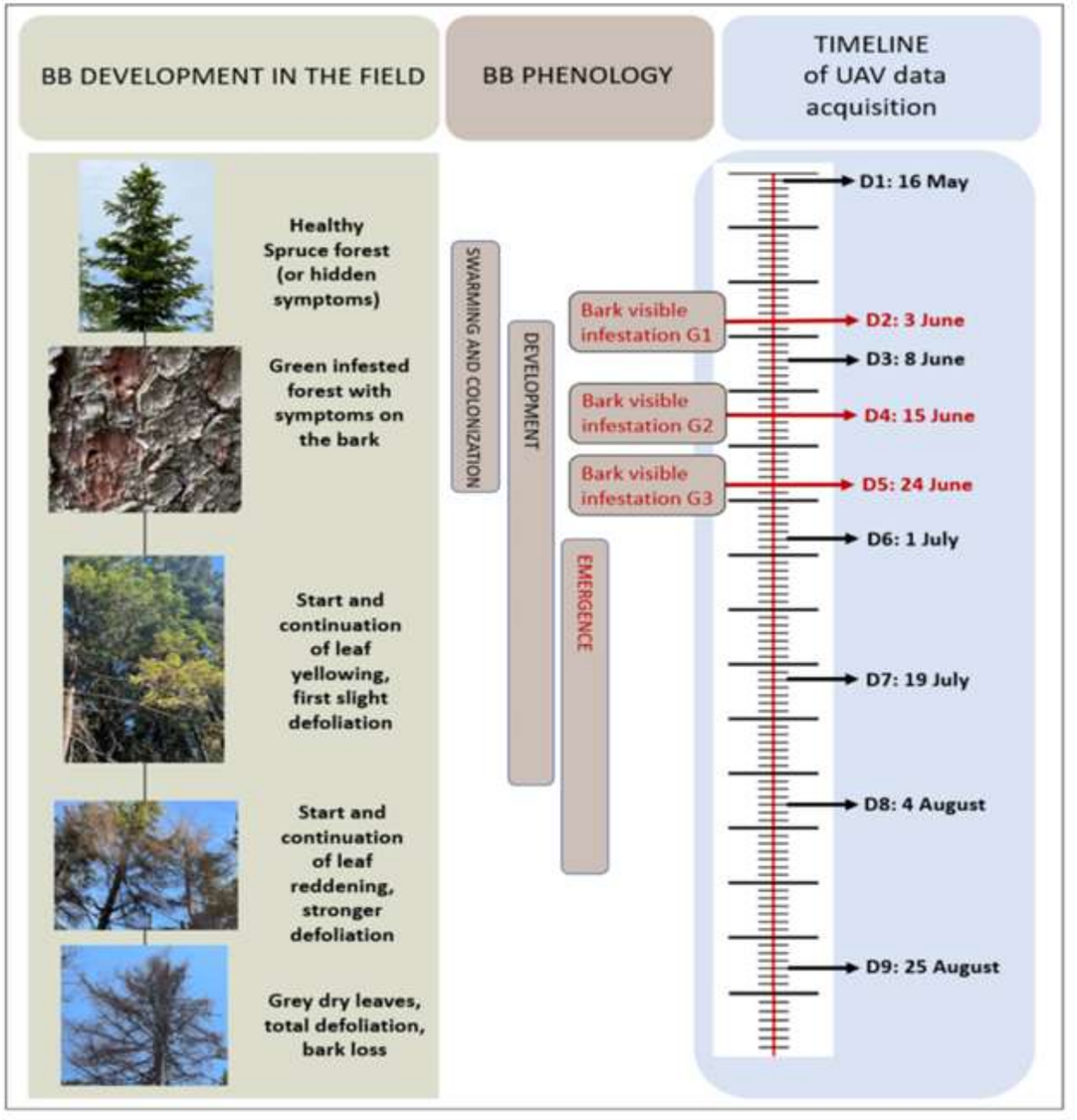
Phantom 4 Multispectral

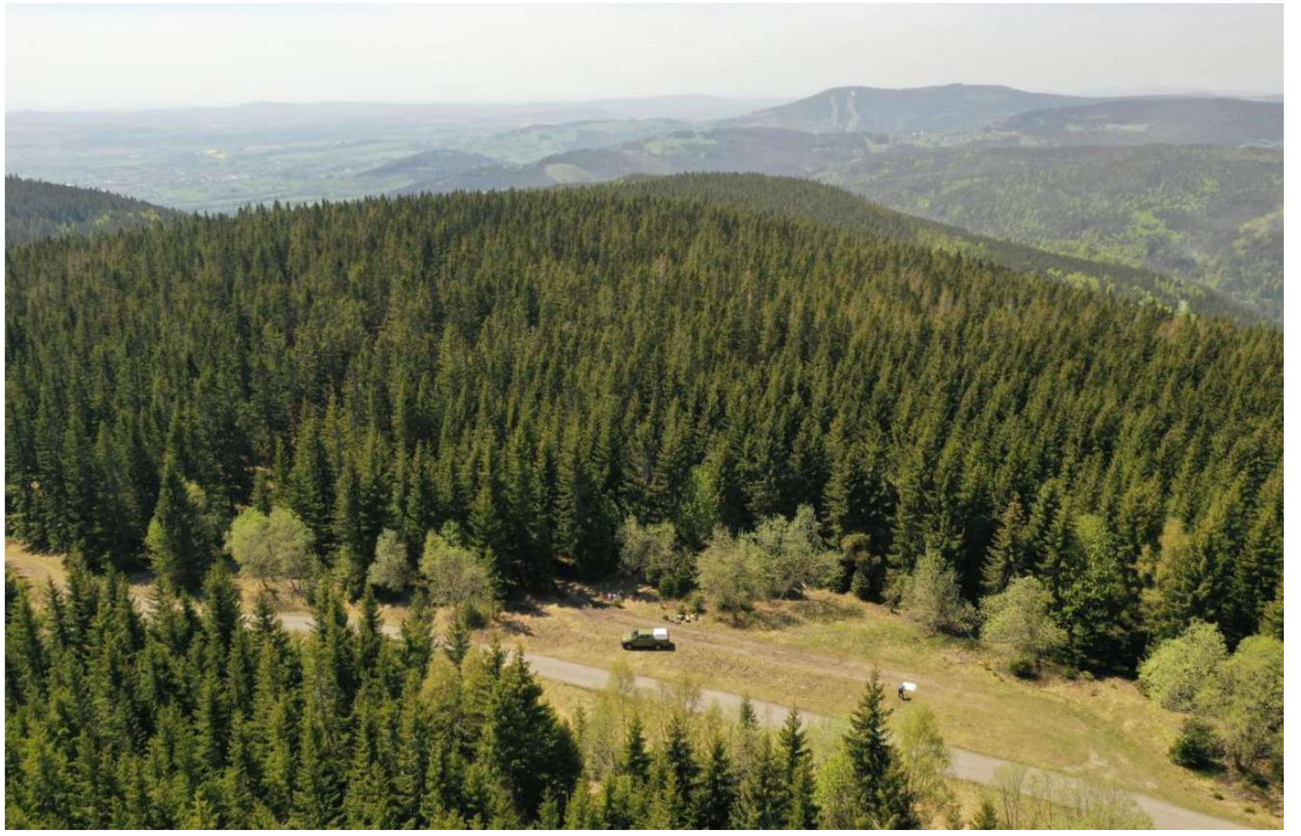
DJI Matrice 600 with NANO camera

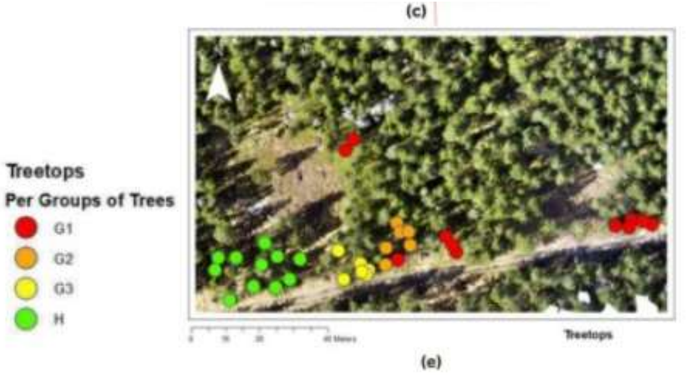
16-may — 03-june — 08-june — 15-June

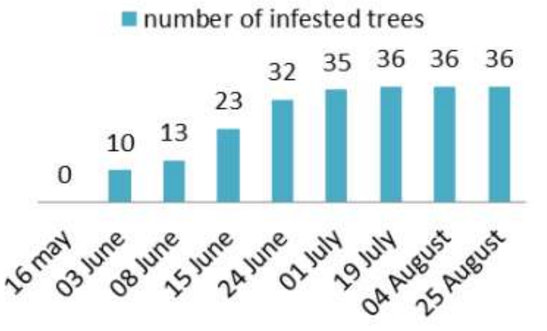
01-July — 19-July — 24-June — 04-August — 25-August

Data collection

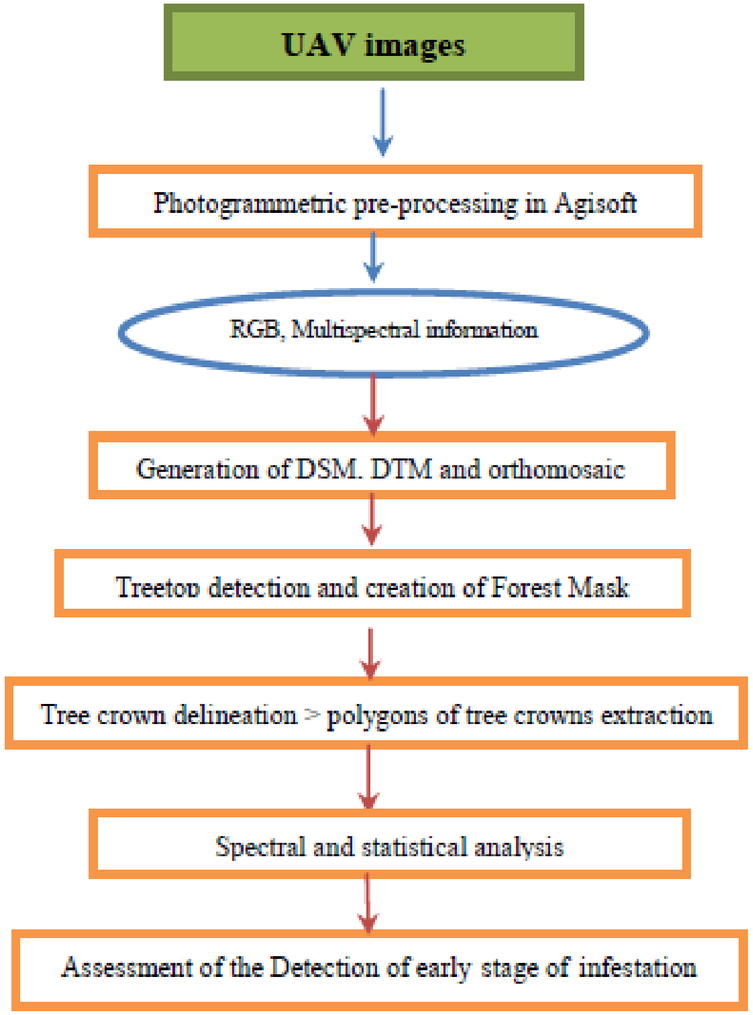






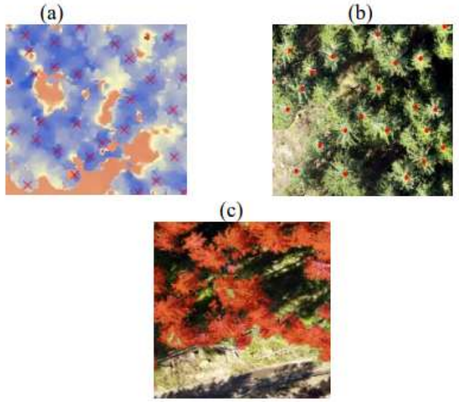


Multispectral data – methods



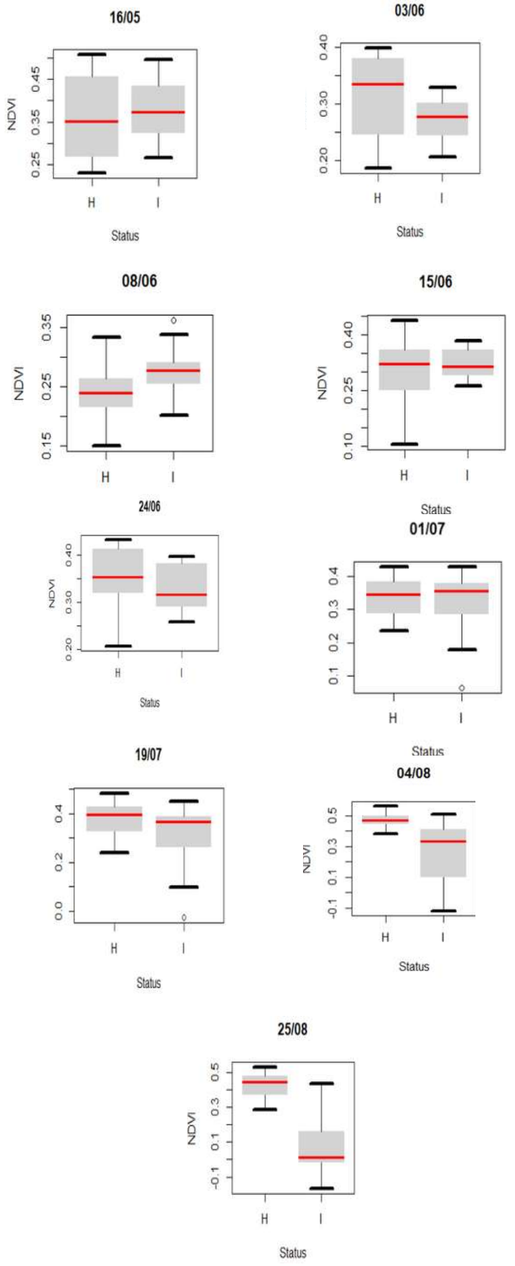
- **Spectral profiles** of each infested tree **were examined**
- **Samples** of **20 infested and 20 healthy trees** **were selected** for each time period (trees with drought stress or without visible symptoms **were excluded**)
- **Normality of spectral data was tested** using the **Shapiro–Wilk test**
- **Significance between groups was assessed** using a **t-test (normal data) or Wilcoxon rank-sum test (non-normal data)**
- **Variance analysis (p = 0.01) was applied** to compare spectra and identify sensitive spectral bands/features across time periods

Results of Automatic treetop detection on DSM and RGB orthomosaic (a,), and Forest Mask (c)



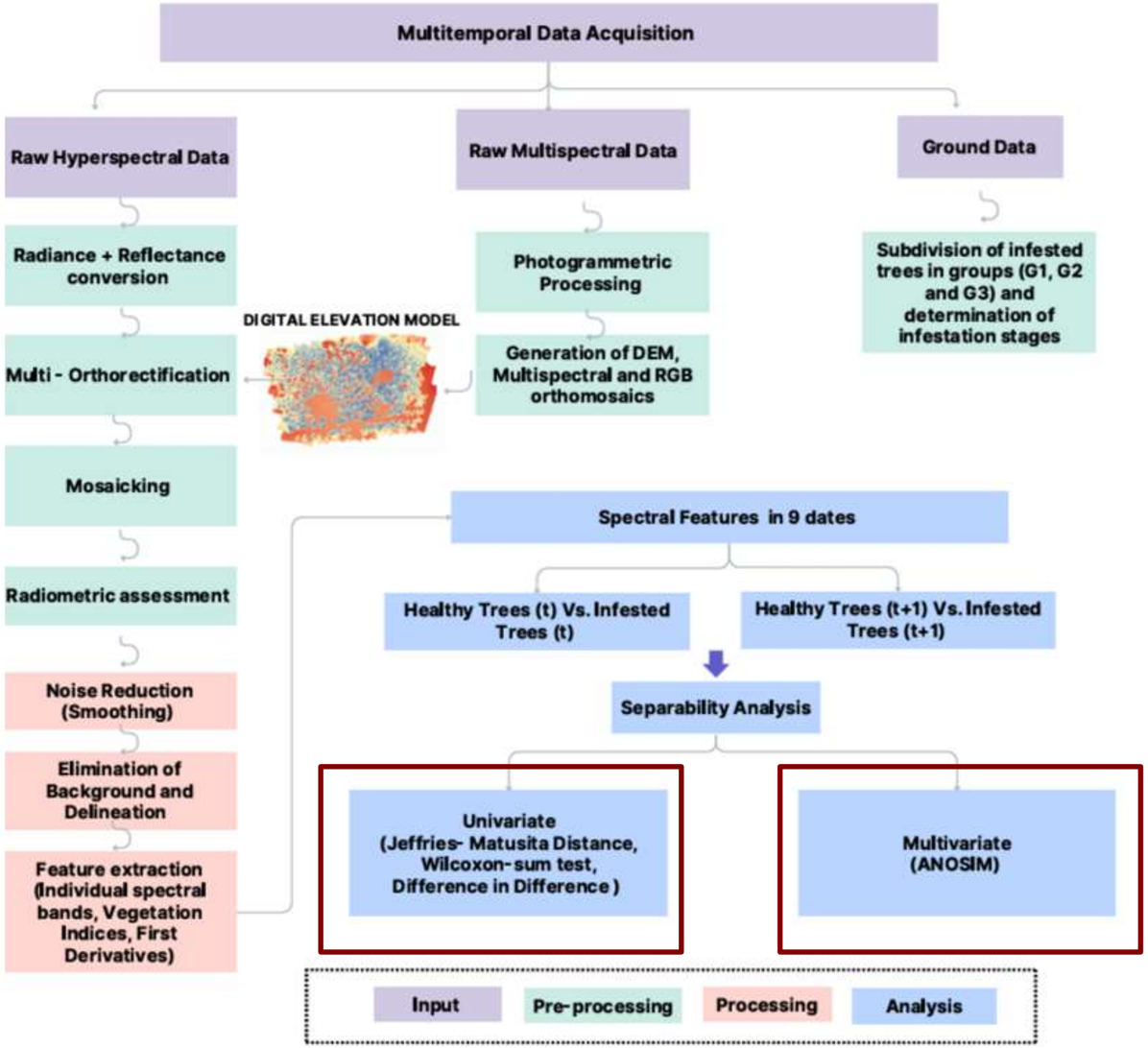
Multispectral data – results

- **First period (May–June):** no clear separability; spectral fluctuations due to **bark beetle attack symptoms** (flowering, new shoots)
- **Second period (July): no class separability** in 5 bands and NDVI
- **Third period (August): clear separability** in Red, RedEdge, NIR bands
- **Best detection** of tree vitality at **end of summer** (late July–early August)
- **Distinction improves over time**, especially in Red, RedEdge, NIR; not possible in **green stage** (spring/early summer)
- **No improvement** in detecting green attack despite **high spatial resolution** and careful pre-processing
- **Hyperspectral imagery** recommended for **early/precise detection** during green stage

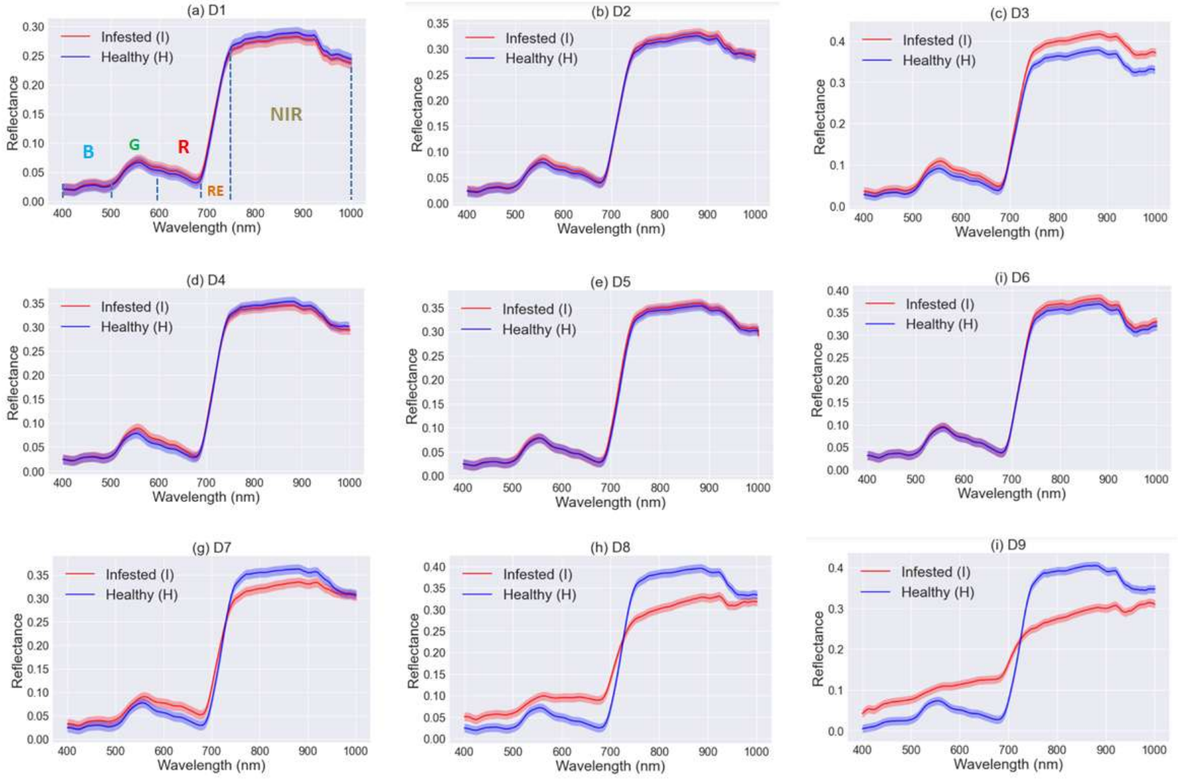


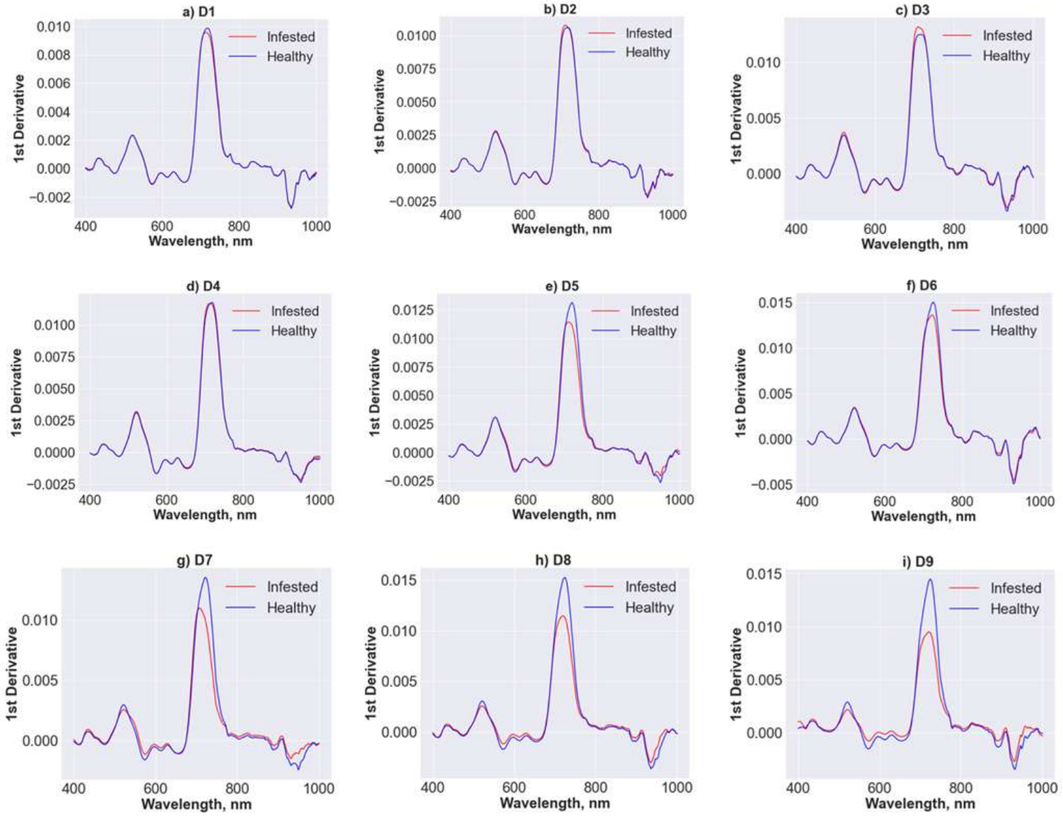
DATE	P-value (NDVI)
16/05	0.6316
03/06	0.05225
08/06	0.05618
15/06	0.4881
24/06	0.4488
01/07	0.7272
19/07	0.1597
04/08	0.002341
25/08	0.007544

Hyperspectral data – methods



Hyperspectral data – results





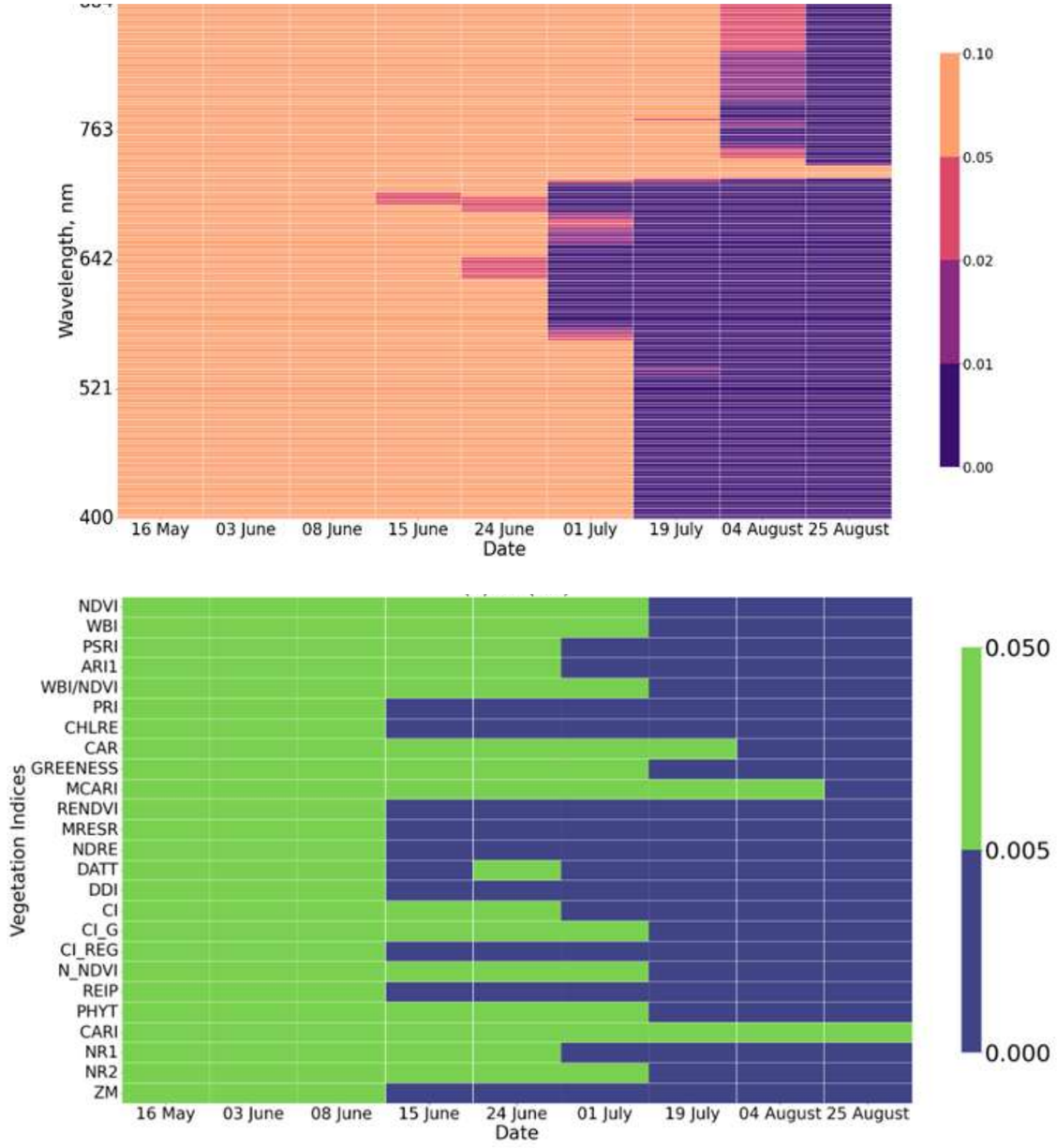
Hyperspectral data – best results

First significant difference on D4: 15 June

Red Edge region

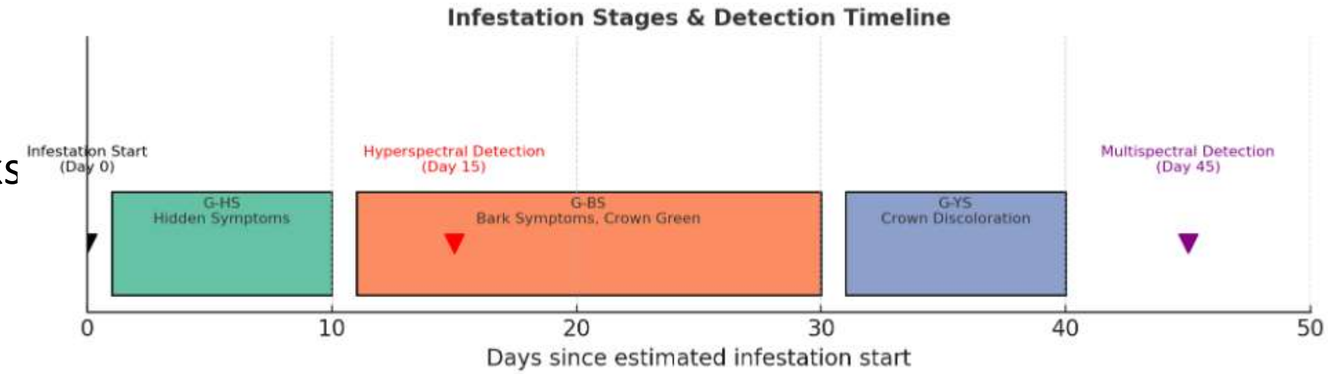
Several spectral indexes

Wilcoxon-sum test



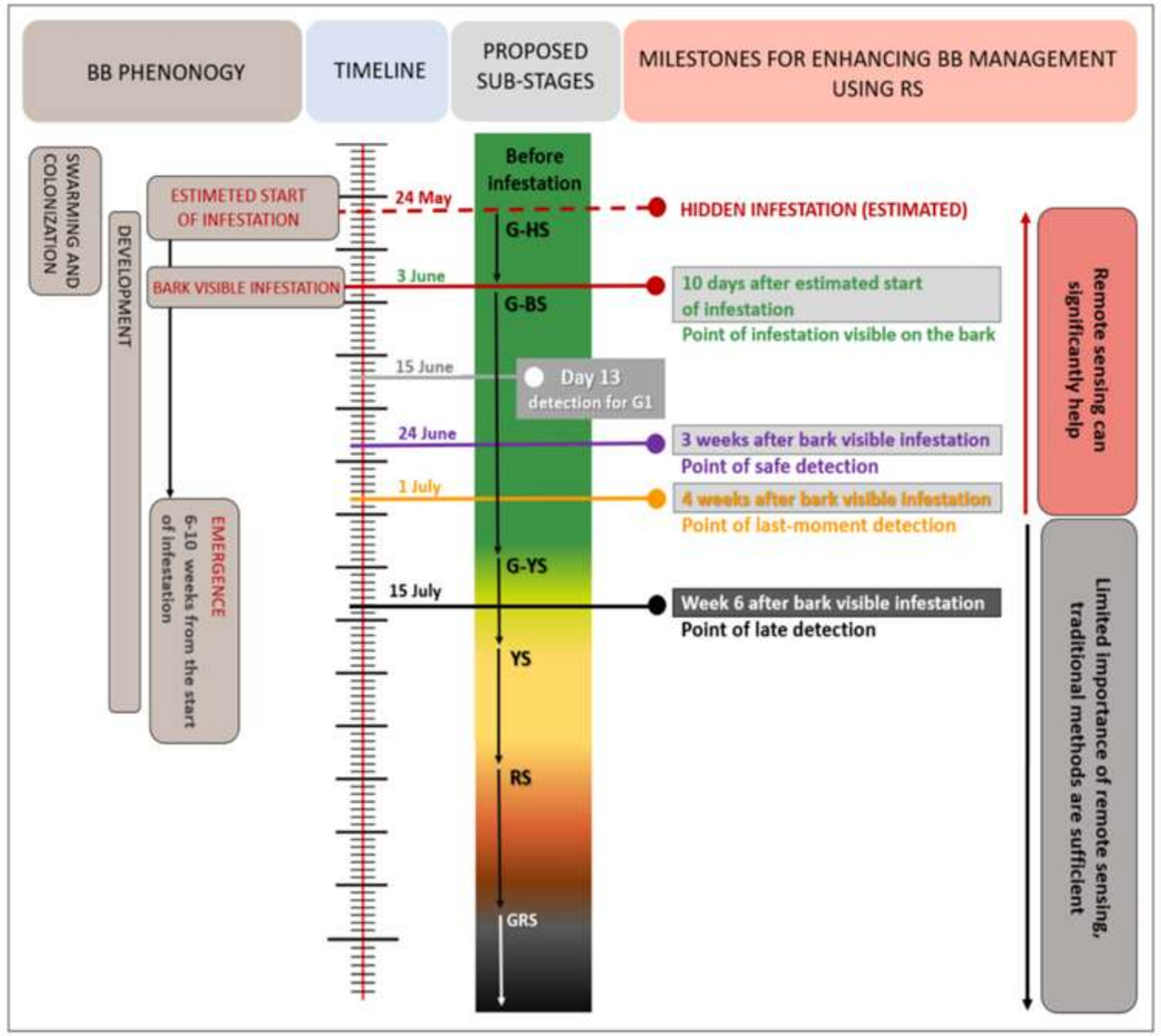
Summary of results

- **Early detection achieved:** Infestation detected **13 days after visible bark symptoms** and **15 days before crown discoloration** using UAV **hyperspectral** imagery
- **Key spectral region & indices: Red-edge wavelengths (692–706 nm)** most effective; sensitive VIs included **PRI, CHLRE, RENDVI, MRESR, NDRE, DATT, DDI, CI-REG, REIP, ZM**. Best methods: **WRST > DiD**
- **Hyperspectral vs. multispectral:** Hyperspectral enabled earlier detection (mid-June) vs. multispectral, which only detected statistically significant changes in **late July/August**
- **New GS sub-stages proposed:**
  G-HS: hidden bark symptoms (days 1–10)
  G-BS: visible bark symptoms, green crowns (≈3 weeks
  G-YS: initial crown discoloration (≈week 5)



- **Timing critical:** Detection **after ~4 weeks** may be too late due to new beetle generation
- **Management implication:** RS detection **within 3 weeks after bark-visible symptoms** is highly effective for outbreak control

Newly proposed substages of green attack stage



We proposed **new sub-stages of the GS** to improve the timing and targeting of RS-based detection:

G-HS – **green hidden symptoms** stage with subtle bark symptoms hidden in the upper parts of the trunk (lasts approx. 1–10 days from the start of infestation)

G-BS – **green** stage with **bark symptoms** on the lower parts of the trunk and crowns remaining green (lasts approx. 3 weeks)

G-YS – **green-yellow stage** with initial crown discoloration (starts approx. in week 5 after bark visible infestation)

RS detection during the late GS, particularly **in the late G-BS stage – later than approx. 4 weeks after bark visible infestation**, may **no longer be timely enough**, especially in cases where **the emergence of a new bark beetle generation** begins within this period

If RS detection occurs within three weeks after bark-visible infestation, it can serve as a **highly effective tool to enhance bark beetle management and prevent further spread of the infestation**

Conclusions

- **We demonstrated the effectiveness of the time series of UAV hyperspectral imagery in detecting the bark beetle inf**estation. The detection occurred while the trees were still in G-BS stage, 15 days before any visible crown discoloration.

- The most effective spectral wavelengths for early detection in our study were located in **the red-edge region (692–706 nm**) and the most sensitive VIs were PRI, CHLRE, RENDVI, MRESR, NDRE, DATT, DDI, CI-REG, REIP, and ZM. The most sensitive and robust detection method was WRST followed by DiD.

- **Hyperspectral data provides enhanced capability for identifying early forest damage** caused by bark beetles compared to multispectral data, likely due to the coarser spectral resolution.

- We proposed **new sub-stages of the GS to improve the timing and targeting of RS-based d**etection: **G-HS** – **green hidden symptoms** stage with subtle bark symptoms hidden in the upper parts of the trunk (lasts approx. 1–10 days from the start of infestation); **G-BS** – **green** stage with **bark symptoms** on the lower parts of the trunk and crowns remaining green (lasts approx. 3 weeks); **G-YS** – **green-yellow stage** with initial crown discoloration (starts approx. in week 5 after bark visible infestation).

- **Detection during the late GS, occurring later than approx. 4 weeks after bark visible infestation, may no longer be timely enough**, especially in cases where the emergence of a new bark beetle generation begins within this period.

- **Detection within three weeks after bark-visible infestation, it can serve as a highly effective tool** to enhance bark beetle management and prevent further spread of the infestation.

Future directions and recommendations

- We recommend that studies focusing on early detection use **clearly defined and standardized sub-stages** of bark beetle infestation, supported by reliable **ground-truth data** and **detailed information on the timing and duration of symptom development in each phenological s**tage. With such methodological precision will it be possible **to robustly demonstrate the ability of remote sensing to detect bark beetle infestation in a timely manner**, for an efficient forest sanitation.

- **Dense time series of hyperspectral data from the start of infestation, with spatial resolutions on the order of centimeters, are recommended** for the effective detection of early-stage bark beetle infestation. This approach currently faces practical limitations, such as high sensor costs, limited spatial coverage, need of an intensive field support, and complex data processing, which constrain its scalability to larger forested areas. Despite these current limitations, our experimental approach represents an important step toward refining early detection methods, which are likely to become increasingly effective and scalable as remote sensing technologies continue to advance.

- **Developing selective, low-cost sensors optimized for the most sensitive spectral regions could significantly enhance early detection capabilities** and improve operational management practices when combined with UAV platforms capable of efficiently covering large forest areas. In light of our results, **the red-edge region appears particularly promising for this purpose** and deserves further exploration.

Papers

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Assessing early bark beetle infestation in Norway spruce using multitemporal hyperspectral UAV imagery: Is detection during the green stage always timely?

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EVALUATION OF THE BARK BEETLE GREEN ATTACK DETECTABILITY IN SPRUCE FOREST FROM MULTITEMPORAL MULTISPECTRAL UAV IMAGERY

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