Carotenoids increase as an indicator of early stress of trees: Estimations using Green Shoulder Indices from Hyperspectral Drone Data and Radiative Transfer Model PROSAIL

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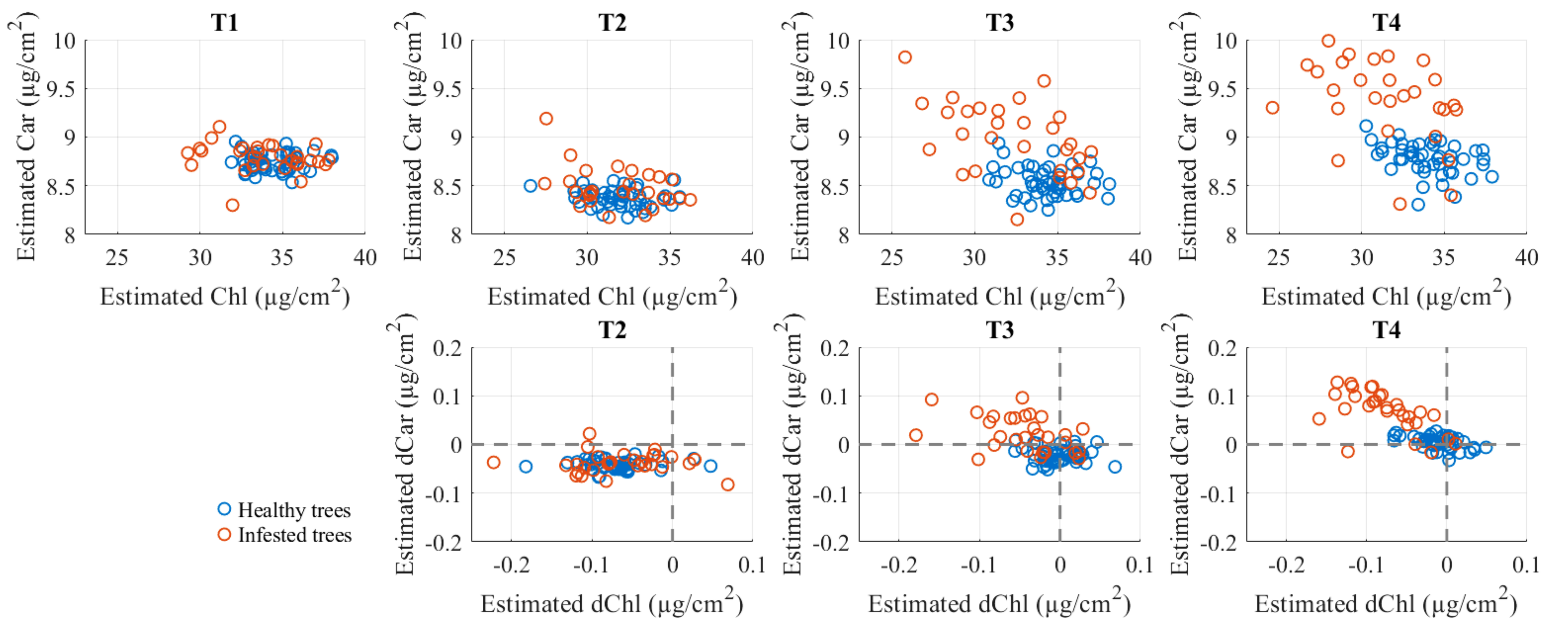
Objectives

- Early tree stress alters pigment composition: **carotenoids may increase**, even before visible symptoms appear.
- Existing remote sensing indices mainly target **chlorophyll (Chl)** via red-edge reflectance.
- This study investigates **green shoulder indices (490–550 nm)** as sensitive indicators of **carotenoid (Car)** changes.
- Combines **hyperspectral drone imagery** with **PROSAIL simulations** to validate sensitivity.

Key results

- Green shoulder indices (especially GSIPExtra) showed **strong correlation with Car** (R^2 = 0.63–0.76).
- **Car/Chl ratio** showed very high R^2 with GSCR1ms and GSIP3PInter (up to 0.98).
- In real-world drone data, **carotenoid increased and chlorophyll decreased** with infestation duration.
- **Carotenoid-based indices** (green shoulder region) **outperformed chlorophyll-based indices** (red-edge region) in separating early-stage infested trees.



Estimated Chl, Car at T1, T2, T3, T4 (figures in the first line), and their changes compared to T1 on real-world data (figures in the second line).

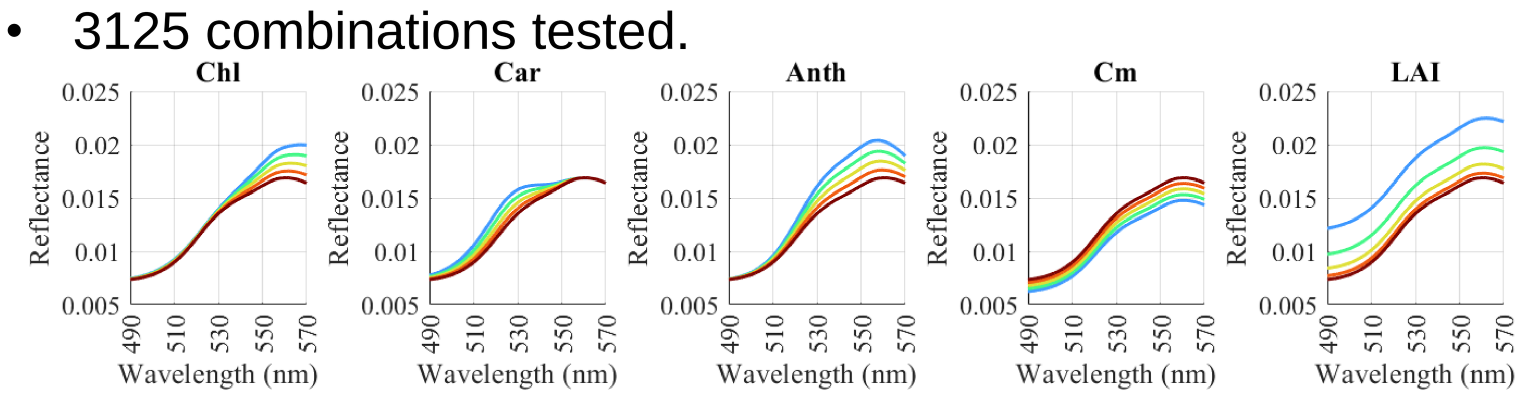
Research highlights

- **Carotenoid content** is a reliable **early stress indicator** detectable via **green shoulder indices**.
- GSIPExtra is a robust index with **strong correlation with carotenoid** and **low sensitivity to chlorophyll**.
- This approach improves **early detection of tree stress** — crucial for managing bark beetle outbreaks.

Methodology

RTM Simulations

- Spectral reflectance simulated with PROSAIL using five variable parameters: Chl, Car, Ant, Dry Matter, LAI.
- 3125 combinations tested.



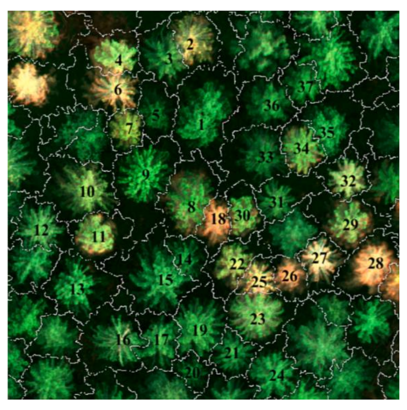
Reflectance, first derivative and second derivative of simulated data with changing parameters one at a time. (spectrum with increasing parameters are presented in blue, green, yellow, orange, and red)

Real-world data

- Drone campaigns over spruce forest infested by bark beetles in southern Finland (T1–T4).
- Hyperspectral data processed (10 cm resolution) and normalized.
- 47 healthy and 29 green-attacked trees selected.

Hyperspectral drone

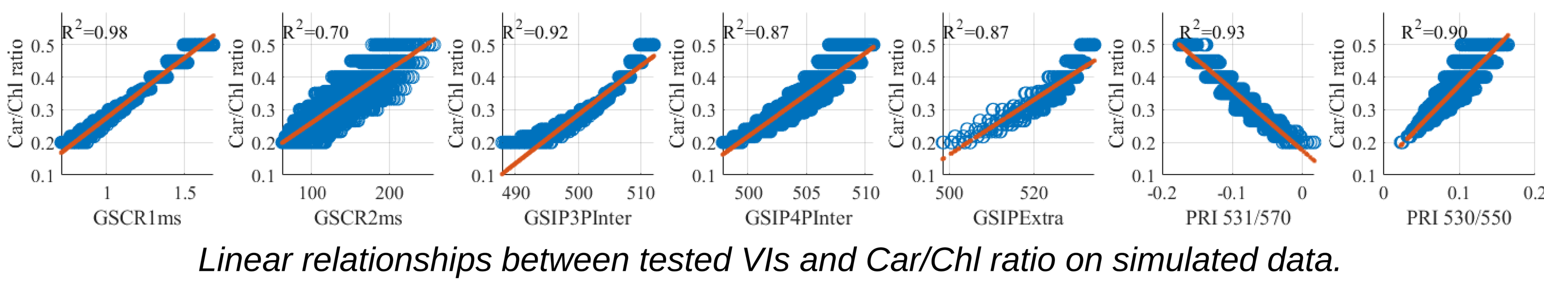
Trees attacked by spruce bark beetle



Tree crowns segments

Vegetation Indices

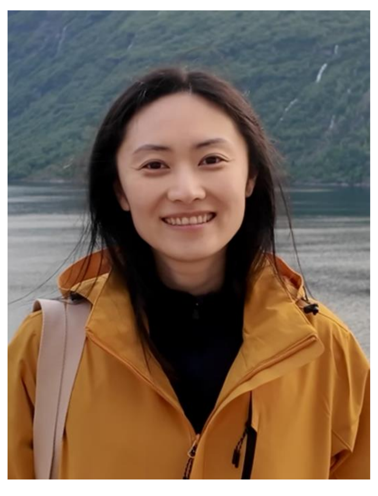
- Green shoulder and red-edge indices computed.
- Linear models established from simulation to estimate Chl and Car in real data.



Linear relationships between tested VIs and Car/Chl ratio on simulated data.

Vegetation indices developed and used to estimate Car and Chl

VIs	Abbreviation	Reflectance at wavelengths	Equation
Green shoulder curvature ratio 1	GSCR1ms	R1, R2, R3, and W1, W2, W3 are reflectance and wavelengths at 490 nm, 530 nm, 560 nm	$\frac{R3 - R2 + 0.01}{R2 - \frac{R1 + R3}{2} + 0.01}$
Green shoulder curvature ratio 2	GSCR2ms	R1, R2, R3, and W1, W2, W3 are reflectance and wavelengths at 490 nm, 530 nm, 560 nm	$\frac{R3 - R2 + 0.01}{(R2 - R1) \times \left(R2 - \frac{R1 + R3}{2} + 0.01\right)}$
Green shoulder inflection position, 3 point interpolation	GSIP3PInter	R1, R2, R3, and W1, W2, W3 are reflectance and wavelengths at 490 nm, 530 nm, 560 nm	$W2 + (W3 - W2) \times \frac{\frac{R1 + R3}{2} - R2 - 0.01}{R3 - R2 + 0.01}$
Green shoulder inflection position, 4 point interpolation	GSIP4PInter	R1, R2, R3, R4, and W1, W2, W3, W4 are reflectance and wavelengths at 490 nm, 520 nm, 545 nm, 560 nm	$W2 + (W3 - W2) \times \frac{\frac{R1 + R4}{2} - R2 - 0.01}{R3 - R2 + 0.01}$
Green shoulder inflection position, extrapolation	GSIPExtra	R1, R2, R3, R4, and W1, W2, W3, W4 are reflectance and wavelengths at 490 nm, 520 nm, 545 nm, 560 nm	m1=(R1-R2)/(W1-W2) c1=((R1+R2)-(W1+W2) × m1)×0.5 m2=(R3-R4)/(W3-W4) c2=((R3+R4)-(W3+W4) × m2)×0.5 GSIPExtra=(c2-c1)/(m1-m2)
Photochemical Reflectance Index	PRI 531/570	R1, R2, and W1, W2, are reflectance and wavelengths at 531 nm, 570 nm	$\frac{R1 - R2}{R1 + R2}$
Photochemical Reflectance Index	PRI 530/550	R1, R2, and W1, W2, are reflectance and wavelengths at 531 nm, 570 nm	$\frac{R1 - R2}{R1 + R2}$
Red edge inflection position, 3 point interpolation	REIP3PInter	R1, R2, R3, and W1, W2, W3 are reflectance and wavelengths at 670 nm, 740 nm, 780 nm	$W2 + (W3 - W2) \times \frac{\frac{R1 + R3}{2} - R2}{R3 - R2}$
Red edge inflection position, 4 point interpolation	REIP4PInter	R1, R2, R3, R4 and W1, W2, W3,W4 are reflectance and wavelengths at 670 nm, 700 nm, 740 nm, 780 nm	$W2 + (W3 - W2) \times \frac{\frac{R1 + R4}{2} - R2}{R3 - R2}$
Red edge inflection position, extrapolation	REIPExtra	R1, R2, R3, R4, and W1, W2, W3, W4 are reflectance and wavelengths at 670 nm, 700 nm, 740 nm, 780 nm	m1=(R1-R2)/(W1-W2) c1=((R1+R2)-(W1+W2) × m1)×0.5 m2=(R3-R4)/(W3-W4) c2=((R3+R4)-(W3+W4) × m2)×0.5 GSIPExtra=(c2-c1)/(m1-m2)



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A **remote sensing** scientist leading a dedicated research team on **forest health and stress dynamics**, developing advanced Earth Observation techniques—including hyperspectral and multispectral drone imaging, satellite data, and LiDAR—to understand how forests respond to climate-driven stressors such as **drought, insect outbreaks, and diseases**.

See more details about green shoulder indices

See more details about ongoing projects

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