SPECTRAL CHARACTERISTICS OF VEGETATION AS INDICATORS OF EARLY STRESS IN FOREST ECOSYSTEMS: A LITERATURE REVIEW

Mihaela Tsvetkova, Lachezar Filchev

Space Research and Technology Institute – Bulgarian Academy of Sciences
e-mail: mtsvetkova@space.bas.bg

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Abstract: *Early detection of stress in forest ecosystems is a prerequisite for timely action against pests, diseases and drought. This literature review synthesizes evidence on the spectral characteristics of vegetation as indicators of early stress, with emphasis on coniferous forests and Norway spruce (Picea abies) stands attacked by the European spruce bark beetle (Ips typographus). It examines the physiological mechanisms underlying vegetation spectral responses, the sensitivity of the visible, red-edge, near-infrared (NIR) and shortwave-infrared (SWIR) regions, and the application of vegetation indices and different remote-sensing platforms. The reviewed studies indicate that the red and SWIR regions and the red edge have considerable potential for distinguishing stressed from healthy stands, although their performance depends on the sensor, observation timing and scale of analysis. Findings for the NIR region are less consistent, while spectral differences may occur before bark beetle attack, limiting their interpretation as specific evidence of infestation. The review outlines key limitations of current approaches and identifies priorities for future research, including multitemporal analysis, integration of remote-sensing data with field observations, and improved discrimination between biotic and abiotic stress.*

СПЕКТРАЛНИ ХАРАКТЕРИСТИКИ НА РАСТИТЕЛНОСТТА КАТО ИНДИКАТОРИ ЗА РАНЕН СТРЕС В ГОРСКИ ЕКОСИСТЕМИ: ЛИТЕРАТУРЕН ОБЗОР

Михаела Цветкова, Лъчезар Филчев

Институт за космически изследвания и технологии – Българска академия на науките
e-mail: mtsvetkova@space.bas.bg

Ключови думи: *Ранен стрес, спектрални характеристики, червен ръб, SWIR,* Ips typographus*, обикновен смърч, вегетационни индекси*

Резюме: *Ранното откриване на стрес в горските екосистеми е предпоставка за навременни мерки срещу вредители, болести и засушаване. Настоящият литературен обзор обобщава данни за спектралните характеристики на растителността като индикатори за ранен стрес, с акцент върху иглолистните гори и насажденията от обикновен смърч (Picea abies), нападани от европейския смърчов кожояд (Ips typographus). Разгледани са физиологичните механизми, определящи спектралния отговор на растителността, чувствителността на видимата област, червения ръб, близката инфрачервена (NIR) и късовълновата инфрачервена (SWIR) област, както и приложението на вегетационни индекси и различни дистанционни платформи. Анализираните изследвания показват, че червената и SWIR областта и червеният ръб имат значителен потенциал за разграничаване на стресирани от здрави насаждения, но ефективността им зависи от сензора, времето на наблюдение и мащаба на анализа. Резултатите за NIR са по-неоднозначни, а спектрални различия могат да се наблюдават още преди нападението от кожояда, което ограничава възможността те да бъдат интерпретирани като специфичен признак за заразяване. Обобщени са основните ограничения на съвременните подходи и са очертани насоки за бъдещи изследвания, включително използване на многовременни серии, комбиниране на дистанционни данни с наземни наблюдения и разграничаване на биотичния от абиотичния стрес.*

1. Introduction

Climate change and global trade increase the vulnerability of forests to disturbances, including diseases caused by fungi, bacteria, viruses and nematodes [1], while droughts, temperature extremes and heat waves become more frequent and severe [2]. The European spruce bark beetle (*Ips typographus*) is a typical example: it has killed more than 150 million m³ of forest in Europe over the last 50 years and in Sweden the affected volume rose from 3–4 million m³ in 2018 to 7 million m³ in 2019 [3]. Infested trees must be removed before the beetles leave the bark, which generally happens before the end of June [3]. Attacks are divided into three stages: green attack, without abnormal visible colours in the crowns; red attack, with yellowing or reddening; and grey attack, with progressive needle loss [3]. At the green-attack stage crowns show no significant colour change in the visible spectrum [3]. Field mensuration is the most accurate way to determine the stage of infection, but it is logistically difficult, time-consuming and expensive [1], whereas remote sensing can record short-term stress dynamics that ground methods cannot capture cost-effectively [4]. This paper summarises what is known about the spectral characteristics of vegetation as early-stress indicators, mainly in conifers, and outlines contradictions and gaps.

2. Physiological and optical basis

Leaf and needle reflectance is formed in three regions: the visible (VIS, 400–700 nm), where low reflectance results from pigment absorption; the near-infrared (NIR, 700–1100 nm), where high reflectance depends on cell structure; and the shortwave infrared (SWIR, 1100–2500 nm), where reflectance is reduced by absorption by water and biochemical compounds (Fig. 1) [1]. The red edge, the sharp rise between chlorophyll absorption in the red and NIR scattering, lies between 680 and 750 nm [5] and depends on chlorophyll content and stress [1].

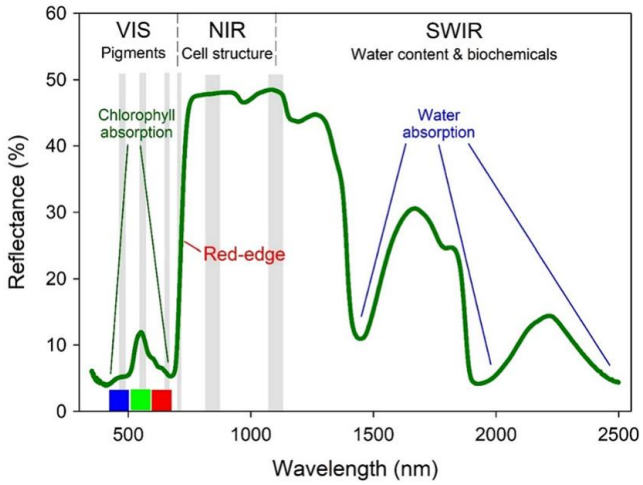


Fig. 1. Typical reflectance profile of healthy vegetation (350–2500 nm) with the VIS, NIR and SWIR regions, chlorophyll and water absorption and the red edge. Source: [1], Fig. 2, p. 23; reproduced under CC BY 4.0.

Stress reduces chlorophyll, which lowers absorption in the visible region and raises reflectance, particularly in the red band [6]. Differences between healthy and stressed vegetation are most evident in the green peak and the red edge, whereas the chlorophyll well and the NIR plateau may initially show no change [5]. The red-edge inflection point shifts towards shorter wavelengths under stress; Rock et al. (1988), reported a shift of about 5 nm in declining spruce and fir. Water affects reflectance mainly in the SWIR, but Carter (1993), considered leaf water content a less useful stress indicator than chlorophyll, consistently apparent only under advanced dehydration. The response is also not specific: similar spectral responses were reported for air pollution, herbicides, competition, dehydration, senescence and poor soils [5]. Infestation of *Picea abies* by bark beetles reduces chlorophyll and photosynthesis, but soil limitations or acid rain can cause the same symptoms, so the cause can be separated only with information on the duration and intensity of the process [4].

3. Spectral regions sensitive to early stress

Visible region. Classical laboratory and close-range studies identified the green region (about 560 nm) and the red edge (685–765 nm) as the most promising early indicators [5]. In Sentinel-2 data on spruce, the red band (B4) had the highest separability between healthy and stressed pixels on

most dates, but the lowest in summer (June–August), and its separability was higher in April–May than in June [3].

Red edge. For needles of spruce with 66–70% foliage loss caused by flooding, the most informative range was 701.0–715.7 nm and the band most sensitive to chlorophyll was 715.6 nm (range 709.9–722.1 nm) [7]. In spruce attacked by *I. typographus*, leaf reflectance was higher in the 680–790 nm range, and red-edge reflectance from RapidEye differed significantly on all dates [6]. However, the sensitivity of red-edge bands should not be interpreted as a universal indicator of green attack, because the timing and magnitude of spectral changes depend on the sensor characteristics, observation period and infestation stage [10].

NIR. Results are inconsistent. Stressed plants generally show lower NIR reflectance [2], and a slight decrease in the early NIR is typical of early disease stages [1]. For spruce, however, the NIR bands had the lowest separability [3], while a significant NIR difference appeared only from 2 July [6]. Huo et al. [3] attributed the inconsistency to pixel size, band positions and the share of attacked trees in the sample (about 30% in their plots versus 100% in the studies of Abdullah et al.).

SWIR. Bands sensitive to leaf water content are narrow and centred on 1450, 1940 and 2500 nm [5]. In Sweden, Sentinel-2 bands B11 and B12 had the highest separability, B12 before July and B11 afterwards [3]. In the Bavarian Forest National Park, SPOT-5 SWIR reflectance differed significantly from 11 May, and leaf reflectance of attacked trees was higher at 1110–1490 nm [6]. For diseases, however, SWIR changes are more typical of late stages [1]. The main findings are summarised in Table 1.

The importance of multitemporal analysis is further demonstrated by Jamali et al. [10], who examined Sentinel-2 time series from 2015–2021 together with harvester data in southeastern Sweden. The SWIR bands showed the greatest separation between healthy and attacked pixels, followed by the red-edge and red bands. Change-detection methods identified infestation-related changes in smoothed vegetation-index time series, although detection timing and performance depended on the method and the temporal data available [10].

Table 1. Spectral regions and main findings on early stress in conifers

Region	**Main findings**	**Source**
Green (~ 550–560 nm)	Early indicator in laboratory and close-range studies; 521–571 nm important in ash (VIP > 0.95)	[5, 9]
Red (660–690 nm)	Higher reflectance under stress; B4 most separable on most dates, least in summer	[6, 3]
Red edge (680–760 nm)	Spruce: 701.0–715.7 nm (laboratory); leaf reflectance higher at 680–790 nm; inflection point shifts to shorter wavelengths in decline	[7, 6, 5]
NIR (760–1000 nm)	Inconsistent: lowest separability in [3]; significant from 2 July in [6]	[3, 6]
SWIR (1100–2500 nm)	Highest separability (B11, B12) in spruce; significant from 11 May (SPOT-5); late-stage change in diseases	[3, 6, 1]

4. Studies on spruce and the spruce bark beetle

Abdullah et al. [6] monitored 66 healthy and 54 attacked spruce trees in the Bavarian Forest National Park on three dates between 15 May and 10 July 2015. All measured leaf traits (chlorophyll, chlorophyll fluorescence, nitrogen, water content, stomatal conductance) differed significantly ($p < 0.05$), with larger differences on the second and third dates; total chlorophyll was 337, 403 and 399 mg/m² in healthy and 317, 301 and 275 mg/m² in attacked trees [6]. At stand level, NDRE (RapidEye) began to separate healthy and attacked plots from 2 July, about a month earlier than the other indices, while the SWIR-based DSWI and NDWI showed significant differences on 5 June and 10 July [6]. The spectral difference peaked from mid-June to early July [6].

Huo et al. [3] analysed Sentinel-1 and Sentinel-2 data from southern Sweden (2018–2019) with 200 reference pixels interpreted from Pléiades imagery and 78 field plots (38 attacked, 40 healthy), in which the share of attacked trees was 18–60%, on average 30% [3]. Pixel values of stressed forest were significantly higher ($p < 0.05$) throughout the season, including before swarming began in mid-April [3]. The red and SWIR bands showed the highest separability and the NIR bands the lowest (Fig. 2), while radar backscatter contributed only slightly [3].

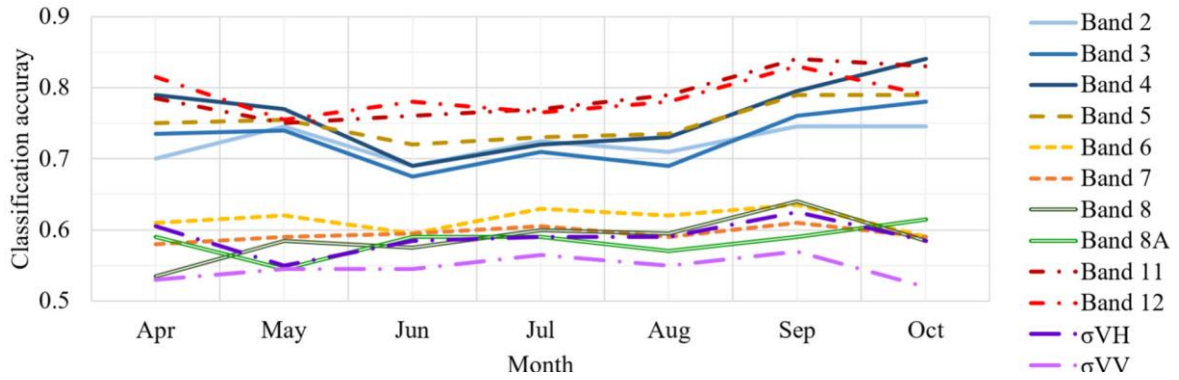


Fig. 2. Separability of individual Sentinel-2 bands and Sentinel-1 backscatter (σVH, σVV) by month, expressed as classification accuracy from linear discriminant analysis. Source: [3], Fig. 8, p. 9; reproduced under CC BY 4.0.

Red and SWIR reflectance are approximately linearly related (R^2 = 0.52 and 0.73 on two dates), and stressed pixels lie further from the origin (Fig. 3) [3]; on this basis the authors proposed the NDRS index. Their key caveat is that spectral differences exist before the attack and should therefore not be interpreted solely as a response to infestation [3]. This agrees with the preference of beetles for weakened trees [3]. Note that stress in the experiments of Masaitis et al. [7] (flooding) and Eitel et al. [8] (girdling) was not caused by beetles.

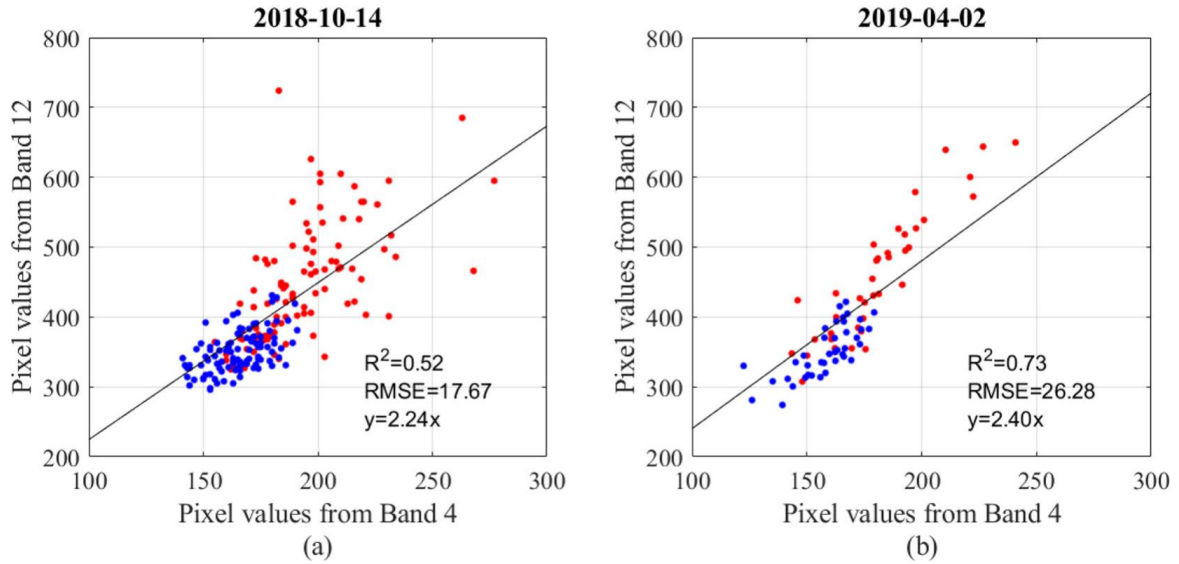


Fig. 3. Sentinel-2 band 4 (red) versus band 12 (SWIR) values for healthy (blue) and stressed (red) forest: (a) 14 October 2018; (b) 2 April 2019. Source: [3], Fig. 7, p. 7; reproduced under CC BY 4.0.

5. Vegetation indices

Huo et al. [3] tested 12 indices: NDWI and RDI gave the highest classification accuracy, followed by DSWI, and indices combining NIR and SWIR bands generally outperformed those using visible bands only, which in turn outperformed those combining NIR and visible bands. Their NDRS index, calculated from Sentinel-2 B4 and B12 as a normalised distance from the origin, was about 10% more accurate than NDWI and RDI in all months (Fig. 4) [3] and reached accuracies of 0.85, 0.80 and 0.89 in April, June and September (threshold 0.5) [3]. NDRS detects stress existing before the attack but is not sensitive to green-attack changes [3].

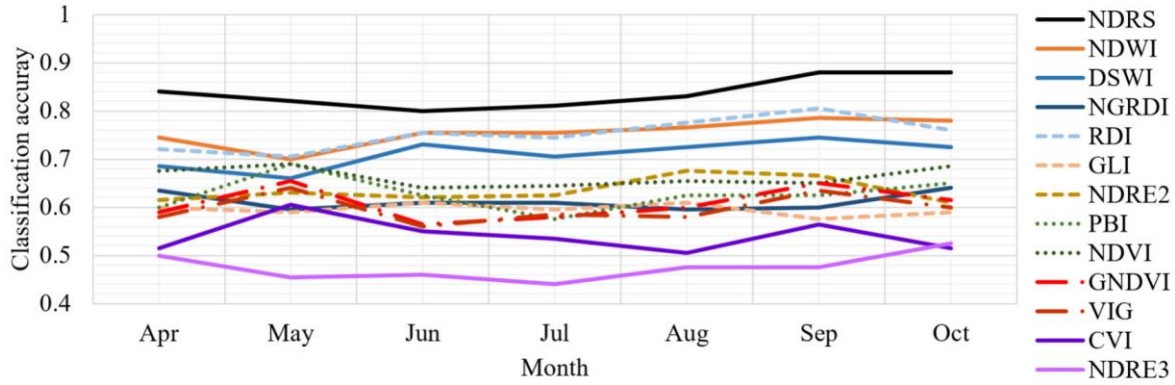


Fig. 4. Separability of 12 vegetation indices and of NDRS by month (classification accuracy from linear discriminant analysis). Source: [3], Fig. 9, p. 9; reproduced under CC BY 4.0.

Red-edge indices respond earlier than red-band indices in broadband satellite data. In RapidEye data of a conifer woodland in New Mexico, NDRE dropped below the no-change zone 13 days after girdling, whereas NDVI and GNDVI responded about 16 days later [8]. Radiative transfer simulation (PROSPECT+SAIL) showed that NDVI saturates above 30 µg/cm² of total chlorophyll, while NDRE remains sensitive across 0–65 µg/cm² [8]. At later stages, with very low chlorophyll and needle loss, NDVI remained responsive and NDRE did not, and applicability to green-attack detection remains untested [8]. A review of forest water stress also found that simple water indices such as NDWI and SIWSI give unsatisfactory results for forest objects, and that widely used NDVI and EVI record damage but do not allow early detection [2].

6. Platforms and sensors

Platforms range from handheld spectrometers to satellites (Fig. 5). In forest water-stress studies satellite data dominate (163 applications versus 27 airborne, 23 ground-based and 11 UAV), and NIR (167) and visible (147) data are used far more often than hyperspectral data (14) [2]. Satellites provide wide coverage and regular data [2], but limits in spatial, spectral, temporal and radiometric resolution may cause errors in green-attack detection, which is why UAV, airborne and future hyperspectral satellites (EnMAP, CHIME, HyspIRI) are proposed [6].

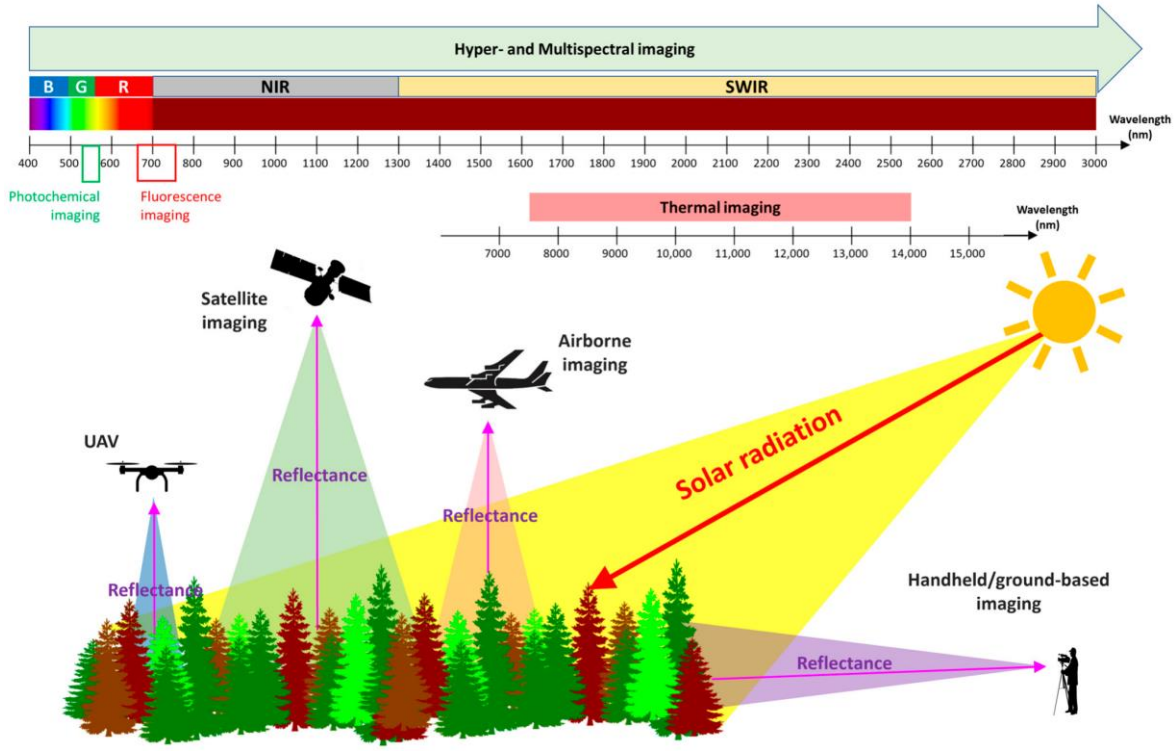


Fig. 5. Main remote sensing platforms and imaging methods for detecting stress in forests. Source: [2], Fig. 2, p. 4 (original by T.S. Le); reproduced under CC BY 4.0.

Hyperspectral data allow selection of the most sensitive bands. Using a UAV hyperspectral camera (400–1000 nm, 150 channels, 5 cm) and LiDAR over ash trees attacked by *Agrilus planipennis*, Zhou et al. [9] identified 678 nm as the most informative band and built NDVI(776,678); combined with LiDAR, the model reached 82.90% overall accuracy and 76.25% for lightly damaged trees, against 50% for LiDAR alone (Fig. 6) [9]. This is a broadleaf species and a different pest, but the study illustrates band selection. For spruce, WorldView-2 multispectral data reached about 75% overall accuracy for three classes, and HyMap hyperspectral data with 4 m pixels 64% [4]; high-resolution multispectral data with decisive bands may thus outperform hyperspectral data [4]. More broadly, a systematic evidence synthesis by Torres et al. [11] found that satellite multispectral data were among the most frequently used technologies in forest-health research, whereas relatively few studies adopted an explicit early-warning perspective. This highlights the need to distinguish retrospective damage mapping from the prospective detection of subtle stress-related changes [11].

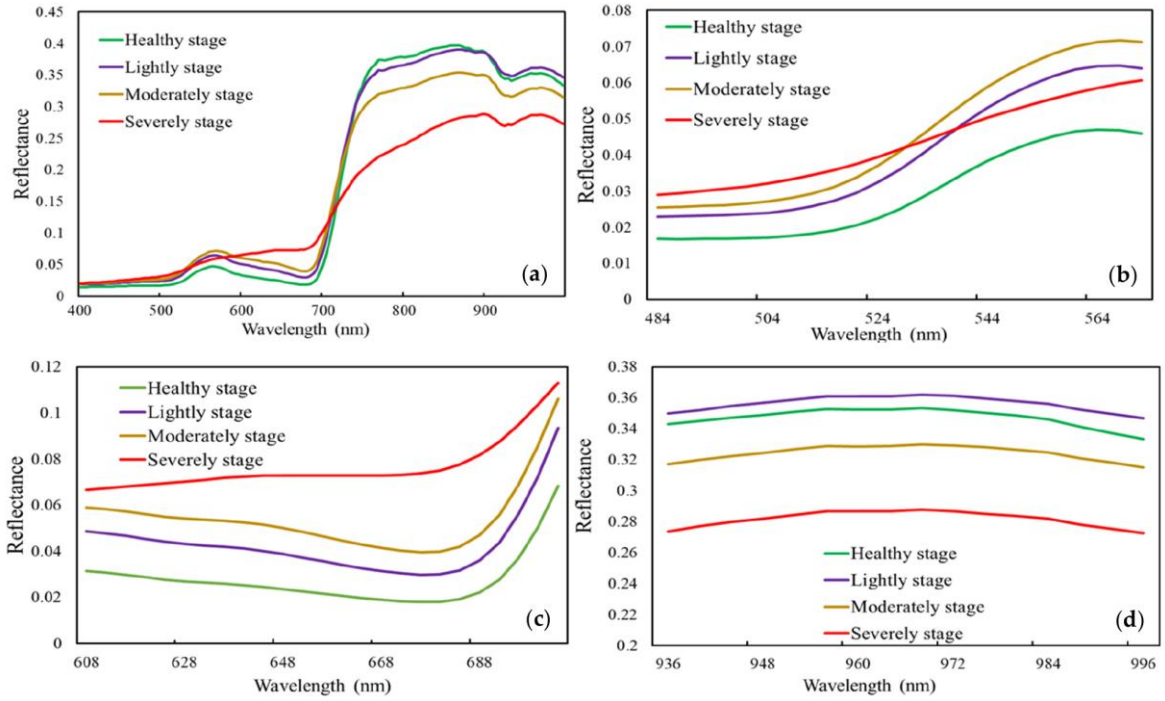


Fig. 6. Mean reflectance of ash canopies at different stages of EAB damage in selected sensitive ranges: (a) 400–1000 nm; (b) 484–571 nm; (c) 608–698 nm; (d) 938–1000 nm. Source: [9], Fig. 10, p. 11; reproduced under CC BY 4.0.

7. Limitations and open questions

First, few studies include spectral data from before the onset of an attack [3], so pre-existing stress cannot be separated from the response to infestation; such differences may be used for early stress detection, but tracing green-attack symptoms requires excluding them [3]. Second, spectral responses are non-specific [4] and natural seasonal changes in chlorophyll and water overlap with stress [5]. Third, larger pixels dilute small early-stage changes [3], and the broad bands of operational satellites mix sensitive and insensitive regions [5]. Fourth, the maximum spectral difference between attacked and healthy spruce (mid-June to early July) [6] comes later than ideal, because adult beetles may leave the bark at the end of June [3]. Finally, many forest diseases and regions remain unexplored, and hyperspectral sensors, long-term monitoring, discrimination of causes and multisensor approaches are needed [1].

8. Conclusion

The reviewed literature indicates that spectral remote sensing provides valuable opportunities for assessing early stress in forest ecosystems, particularly in coniferous stands affected by the European spruce bark beetle (*Ips typographus*). The visible, red-edge and shortwave-infrared (SWIR) regions are the most frequently reported sources of information on stress-related changes in pigment content, canopy structure and water status. In particular, Sentinel-2 studies have demonstrated the potential of red and SWIR bands to distinguish stressed from apparently healthy spruce stands, while red-edge-based indices have shown promising sensitivity to changes in chlorophyll content. However,

no single spectral region or vegetation index can be considered universally optimal. Performance varies with the sensor's spectral and spatial resolution, the timing of observations, the proportion of affected trees within a pixel, and the physiological stage of stress. Evidence from the near-infrared (NIR) region remains less consistent, further demonstrating the importance of interpreting spectral responses in their ecological and observational context.

A major limitation is the lack of specificity of optical responses. Changes in reflectance may result from bark beetle infestation, drought, heat, other biotic agents or their combined effects. Moreover, spectral differences between subsequently attacked and apparently healthy stands may already be present before infestation, indicating that predisposition to attack and the response to a confirmed attack should not be treated as equivalent phenomena. Although such pre-existing differences may be useful for assessing vulnerability, their presence alone does not establish that an infestation has occurred. This distinction is particularly important for green-attack detection, when visible crown symptoms may still be absent and the available spectral signal may be subtle or inconsistent.

Future research should therefore prioritise multitemporal analyses that include observations before and after confirmed attacks, systematic field validation and explicit consideration of seasonal and environmental variability. Combining Sentinel-2 time series with higher-resolution UAV observations, field measurements and relevant climatic and stand-level variables could improve the interpretation of early changes and help distinguish biotic from abiotic stress. Hyperspectral and thermal observations also offer opportunities to investigate more subtle physiological responses, although their practical value must be assessed against data availability, spatial coverage and operational requirements. Future studies should report validation procedures transparently and test their methods across independent sites and observation periods.

Overall, remote sensing should be regarded as a complementary tool for forest-health monitoring rather than a stand-alone means of identifying the causal agent of stress. Its greatest potential lies in detecting changes, tracking their development over time and identifying areas that require targeted field inspection. Progress towards reliable early-warning systems will depend not only on identifying sensitive spectral bands or indices, but also on integrating spectral evidence with ecological processes, field observations and robust validation.

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