S E S 2 0 2 6
Twenty-second International Scientific Conference
SPACE, ECOLOGY, SAFETY
20 – 24 October 2026, Stara Zagora, Bulgaria

ASSESSMENT OF BIOTIC STRESS IN SPRUCE FORESTS USING REMOTE SENSING: A LITERATURE REVIEW

Mihaela Tsvetkova, Lachezar Filchev

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

Keywords: *Norway spruce, biotic stress,* Ips typographus*, fungal decay, remote sensing, Sentinel-2, red-edge, SWIR, time series*

Abstract: *This review synthesizes evidence on remote-sensing assessment of biotic stress in Norway spruce (*Picea abies *(L.) H. Karst.), with emphasis on* Ips typographus *and fungal wood-decay agents. Particular attention is given to the physiological chain linking predisposition, attack, host defence, hydraulic and carbon imbalance, and the subsequent spectral response. The literature indicates that bark beetle attack can alter water status, photosynthetic function and defence before pronounced crown discoloration, whereas root, butt and heartwood rots often develop chronically with weak external symptoms. Red-edge, Near-Infrared (NIR) and Short-Wave Infrared (SWIR) information, temporal trajectories and, where available, canopy temperature can therefore provide complementary evidence of stress, but none is specific to a single causal agent. Sentinel-2 is well suited to regional time-series monitoring, while Unmanned Aerial Vehicle (UAV) and high-resolution satellite data support crown-level reference and validation. For chronic internal decay, multi-temporal data combined with crown structure and Airborne Laser Scanning (ALS) are more appropriate than single-date spectral classification. A suitable operational methodology should therefore combine field-confirmed disturbance stages, multitemporal spectral anomalies, climatic and stand covariates, individual-tree or stand-level spatial units, and spatially independent validation. The review proposes a stage-aware framework for distinguishing predisposition, early attack, active infestation and post-attack decline.*

ОЦЕНКА НА БИОТИЧНИЯ СТРЕС В СМЪРЧОВИ ГОРИ ЧРЕЗ ДИСТАНЦИОННИ МЕТОДИ: ЛИТЕРАТУРЕН ОБЗОР

Михаела Цветкова, Лъчезар Филчев

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

Ключови думи: *Норвежки смърч, биотичен стрес,* Ips typographus*, гъбно гниене, дистанционни изследвания, Sentinel-2, red-edge, SWIR, времеви серии*

Резюме: *Настоящият литературен обзор синтезира научните доказателства относно оценката на биотичния стрес при норвежкия смърч (*Picea abies *(L.) H. Karst.) чрез дистанционни изследвания, с акцент върху* Ips typographus *и гъбните причинители на дървесни гниения. Особено внимание е отделено на физиологичната последователност, свързваща предразположеността, нападението, защитните реакции на гостоприемника, нарушенията във водния и въглеродния баланс и последващия спектрален отговор. Литературните данни показват, че нападението от короядите може да предизвика промени във водния статус, фотосинтетичната функция и защитните механизми на дърветата преди появата на ясно изразено обезцветяване на короната, докато кореновите, комловите и ядровите гниения често се развиват хронично и протичат при слабо изразени външни симптоми. Поради това информацията в областта на червения край на спектъра (red-edge), близката инфрачервена област и късовълновата инфрачервена област, времевите траектории на спектралните показатели и, когато са налични, данните за температурата на короната могат да предоставят допълваща информация за наличието и развитието на стрес, но нито един от тези източници на информация не е специфичен за конкретен причинител. Sentinel-2 е особено подходящ за регионален мониторинг чрез многовременни серии от наблюдения, докато безпилотните летателни апарати (UAV) и сателитните данни с висока пространствена резолюция подпомагат референтната оценка и валидирането на ниво корона. При хронични вътрешни гниения многовременните данни, комбинирани с информация за структурата на короната и данни от въздушно лазерно сканиране (ALS),*

са по-подходящи от класификация, базирана върху еднократно спектрално наблюдение. Следователно подходящата оперативна методология трябва да интегрира потвърдени чрез полеви наблюдения етапи на развитие на увреждането, многовременни спектрални аномалии, климатични и насаждански фактори, пространствени единици на ниво отделно дърво или насаждение и пространствено независимо валидиране. Въз основа на разгледаните научни доказателства е предложена рамка, отчитаща етапа на развитие на стреса, за разграничаване на предразположеността, ранното нападение, активната инфестация и последващия упадък на дърветата.

Introduction

Forest health reflects the interaction between environmental conditions, tree physiology and biotic disturbances. Norway spruce (*Picea abies* (L.) H. Karst.) is sensitive to water and temperature stress, which can reduce stomatal conductance, photosynthesis and water status and weaken constitutive and induced defence mechanisms. Such physiological weakening may increase susceptibility to secondary biotic agents, while pathogens can progressively impair roots, stems or internal wood tissues. Consequently, biotic stress should be considered as a process ranging from physiological disturbance to tissue damage, crown decline and, in severe cases, tree mortality (Singh et al., 2024; Kędziora et al., 2025). Importantly, these processes differ substantially among disturbance agents. Bark beetle infestation, particularly by the European spruce bark beetle (*Ips typographus* L.), may progress relatively rapidly from an inconspicuous green-attack stage to crown decline and mortality, whereas root, butt, stem and heartwood decay may develop over longer periods and remain poorly expressed in the canopy (Dalponte et al., 2022a, 2022b; Allen et al., 2022).

Remote sensing provides spatially extensive and repeated observations of forest condition, but it does not directly detect a pest or pathogen. Spectral, thermal and structural anomalies represent changes in vegetation condition and may therefore have multiple possible causes, including biotic attack, drought, heat or other environmental stressors. This causal ambiguity is particularly important during the early stages of disturbance. In bark beetle infestation, trees may remain visually green while changes in foliar biochemical properties, water status and spectral response have already occurred. Sentinel-2 studies have demonstrated the potential of red-edge, near-infrared (NIR) and shortwave-infrared (SWIR) information, particularly when combined with temporal observations, for detecting such subtle changes before pronounced crown discoloration (Abdullah et al., 2019; Huo et al., 2021; Bárta et al., 2021). In contrast, fungal decay presents a different remote-sensing challenge because internal deterioration may produce weak or delayed canopy signals.

Recent research has therefore increasingly moved from individual spectral indices towards multitemporal analysis, machine learning (ML) and multisource data integration. Satellite time series, particularly Sentinel-2, provide repeated landscape-scale observations, while UAV multispectral or hyperspectral imagery can characterize individual crowns and support targeted validation. Structural information from airborne laser scanning (ALS) and environmental variables can further improve interpretation, especially for disturbances that are not directly expressed in canopy reflectance (Dalponte et al., 2022a, 2022b; Räty et al., 2021; Ecke et al., 2022). However, the transferability of models between sites, years and disturbance stages remains a major limitation, and spatially dependent validation can lead to overestimated model performance (Kautz et al., 2024; Marvasti-Zadeh et al., 2023; Mngadi et al., 2024).

In this review, early detection refers to the identification of biotic disturbance before pronounced visible crown deterioration, whereas green attack specifically denotes the visually green stage of bark beetle infestation. The objective is to summarize and critically evaluate remote-sensing approaches for detecting and assessing biotic stress in spruce forests, with emphasis on the physiological basis of detectable responses and the complementary contribution of spectral, temporal, structural and thermal information. Particular attention is given to bark beetle infestation and fungal decay as biologically contrasting disturbance pathways, and to the integration of remote-sensing observations with field and environmental data for developing reliable and locally transferable monitoring approaches.

Physiological basis of biotic stress

From predisposition to bark beetle-induced decline

The response should be considered as a sequence rather than a single “attack signal”: climatic or site stress → reduced physiological resilience → beetle colonisation → defence activation → disruption of transport and carbon balance → crown response → mortality. Drought and heat reduce stomatal conductance and photosynthetic carbon assimilation. In conifers, water deficit can also reduce resin-based defence by lowering tissue turgor and resin pressure; this can impair the tree’s ability to repel or contain attackers (Singh et al., 2024). At low beetle population density,

I. typographus preferentially colonises weakened hosts, whereas mass attack can overcome the defence of apparently vigorous trees. Successful pioneers produce aggregation pheromones that recruit additional beetles, while associated microorganisms contribute to depletion of host defence (Singh et al., 2024).

Once colonisation is established, feeding and gallery construction in the phloem disrupt transport of assimilates and signalling compounds. The resulting hydraulic and carbon imbalance, together with continued respiration, accelerates depletion of reserves. Reduced water supply and stomatal closure constrain gas exchange; progressive dysfunction is ultimately expressed as needle pigment alteration, reduced foliage water content, defoliation and crown discoloration. Importantly, the timing of visible symptoms is variable. For *I. typographus*, crown colour change may become conspicuous months after attack, so a green crown should not be equated with physiological absence of stress (Singh et al., 2024).

This mechanism explains the remote-sensing sequence. Changes in chlorophyll and pigment balance may affect the visible and red-edge regions; changes in leaf/canopy water content affect NIR/SWIR; structural deterioration becomes increasingly important later. Red-edge observations are therefore attractive for subtle chlorophyll-related changes, while SWIR is particularly relevant to water status (Stone & Mohammed, 2017; Abdullah et al., 2019; Huo et al., 2021). However, these responses are not unique to beetle attack.



Fig. 1. Proposed physiological pathway linking predisposing climatic stress, defence impairment, I. typographus colonisation and the subsequent spectral/thermal response

Chronic fungal decay and weak external symptoms

Root, butt, stem and heartwood rots require a different conceptual model. *Heterobasidion* and *Armillaria* can develop internally and progressively degrade wood while leaving the crown comparatively functional. Consequently, the causal process may be spatially disconnected from the tissue directly observed by optical sensors (Allen et al., 2022; Dalponte et al., 2022a, b). This is why single-date greenness indices are unlikely to provide a reliable diagnostic signal.

Evidence nevertheless indicates that chronic decay can affect crown density, water relations and growth sufficiently to produce subtle remote-sensing differences. Allen et al. (2022) used UAV hyperspectral and ALS data to classify root, butt and stem rot in Norway spruce, obtaining up to 75.6% accuracy with 490-band hyperspectral imagery, although κ was only 0.24. Dalponte et al. (2022a) reported 62.0–65.5% overall accuracy for wood-decay detection using airborne hyperspectral and ALS data, while Dalponte et al. (2022b) achieved a balanced accuracy of 56.3% using three years of 3-m PlanetScope/Dove data and individual-tree crowns. The relatively modest accuracies are informative: internal decay is detectable only indirectly and requires structural and temporal context.

Thus, bark beetle attack is better represented as an acute disturbance with a potentially short pre-visual window, whereas wood decay is predominantly chronic and may require long-term trajectories. This distinction should determine both sensor selection and the target variable.

Remote-sensing methodology

Sensor selection and spatial scale

For regional monitoring, Sentinel-2 offers an effective compromise between coverage, revisit frequency and spectral configuration. Its red-edge and SWIR bands are particularly relevant to chlorophyll and water-status changes. WorldView-2 and other high-resolution satellite systems can improve crown separation (Immitzer & Atzberger, 2014), while UAV multispectral data provide flexible, high-resolution acquisitions for individual-tree validation and green-attack studies (Huo et al., 2023; Klouček et al., 2024). UAV studies should be viewed primarily as a means of capturing fine spatial and temporal reference information rather than as a replacement for regional satellite monitoring.

Thermal observations are complementary because stomatal closure reduces evaporative cooling and can increase canopy temperature. A thermal anomaly therefore provides physiological information that may precede visible discoloration, but temperature is strongly affected by radiation, air temperature, wind, humidity and acquisition time (Smigaj et al., 2024). Hyperspectral data are valuable for mechanistic research and biochemical discrimination but are less practical for routine regional monitoring.

Table 1. Relative strengths and limitations of remote-sensing approaches for assessing spruce biotic stress

Approach	Main advantage	Main limitation	Typical contribution
Sentinel-2 multispectral	Wide coverage; frequent observations; red-edge and SWIR information	10–60 m band-dependent resolution; mixed crowns	Regional monitoring and time-series analysis
High-resolution satellite	Detailed crown structure	Higher cost and/or lower temporal availability	Individual-tree and small-cluster mapping
UAV multispectral	Very high spatial resolution; flexible timing	Limited coverage; field logistics	Early green-attack detection and crown-level analysis
Hyperspectral	Fine spectral information	Large data volume; limited operational coverage	Physiological and biochemical stress discrimination
Thermal	Information on canopy temperature and water stress	Atmospheric and illumination effects	Water-stress and temperature-response assessment

Spectral indicators and time series

NDVI remains useful for describing broad canopy condition, but it can saturate in dense spruce stands and may be insensitive to weak early stress. Red-edge indices such as NDRE and chlorophyll-sensitive bands can capture changes that are less apparent in the visible domain. Moisture-sensitive NIR-SWIR combinations and NDRS have shown potential for early *I. typographus* stress detection (Huo et al., 2021). The key methodological principle, however, is not to search for a universal “bark beetle index”.

Temporal anomalies are more defensible than single-date thresholds. Bárta et al. (2021) showed that seasonal trajectories can outperform individual observations for separating healthy and green-attack spruce. A suitable workflow is therefore: (1) construct a cloud-screened seasonal Sentinel-2 time series; (2) normalize observations to phenological stage; (3) calculate red-edge, NIR and SWIR indicators; (4) derive change metrics relative to a healthy reference trajectory; and (5) combine these anomalies with climate and stand variables. This approach explicitly asks whether a tree or stand deviates from its expected seasonal behaviour.

Field reference data and spatial units

Reliable reference data are the critical bottleneck. Each observation should include species, geographic position, disturbance agent where known, infestation/decay stage, date of field assessment and, ideally, repeated observations. For bark beetles, “healthy”, “green attack”, “visible decline” and “dead/post-attack” should be separated rather than collapsed into healthy/damaged classes. For fungal decay, reference data should distinguish confirmed decay from visually healthy trees, preferably using harvest, increment boring or other pathology-based evidence.

At individual-tree scale, ITC delineation can be based on ALS/CHM or photogrammetric data and should be checked against field positions. For stand-level modelling, the sampling unit should match the intended management application. Räty et al. (2021) demonstrated that spatial validation strongly affects performance: for butt-rot mapping, pseudo-R^2 decreased from 0.60 with stand-based validation to 0.37 with spatially distinct cluster validation. This shows why random pixel splits can produce overly optimistic results when neighbouring samples are correlated.

Modelling and validation

The appropriate modelling strategy is a hierarchical one. First, identify physiological anomaly; second, classify disturbance stage; third, estimate the most likely biotic driver using field and environmental context. Random Forest, SVM and related methods can integrate spectral, temporal, topographic and stand variables, while deep learning is most useful when large labelled datasets are available (Marvasti-Zadeh et al., 2023; Mngadi et al., 2024). Model performance should be evaluated with spatially independent hold-out sites and, where possible, different years. Accuracy alone is insufficient; balanced accuracy, F1-score, sensitivity to the early-attack class and confusion between abiotic and biotic stress should also be reported.

A practical framework for spruce forests is therefore: Sentinel-2 time series for regional screening; climate variables such as precipitation, temperature and VPD to characterize predisposition; ALS/CHM or high-resolution imagery for crown structure; UAV multispectral/thermal observations for targeted validation; and field pathology/forest-health surveys for causal attribution. This reduces the risk of interpreting drought or heat stress as a bark beetle signal.



Fig. 2. Proposed methodological framework for stage-aware and spatially transferable monitoring of spruce biotic stress

Evidence across disturbance types

The literature suggests that no single sensor or indicator is optimal for all forms of biotic stress. For *I. typographus*, Sentinel-2 red-edge/SWIR time series can detect green-attack-related changes before strong discoloration (Abdullah et al., 2019; Huo et al., 2021; Bárta et al., 2021), while UAV multispectral observations increase crown-level sensitivity (Huo et al., 2023; Klouček et al., 2024). For internal wood decay, ALS and multi-temporal optical information are more important because the causal process is not directly visible in the canopy (Dalponte et al., 2022a, b; Räty et al., 2021). UAV hyperspectral data can provide higher biochemical sensitivity but require more extensive calibration and are less scalable (Allen et al., 2022).

The systematic review of UAV forest-health studies by Ecke et al. (2022) further supports the importance of flexible high-resolution acquisitions, while emphasizing that forest-health applications remain methodologically heterogeneous. Thermal remote sensing provides an additional physiological dimension, but its operational use in forest pathology is less mature than multispectral monitoring (Smigaj et al., 2024). Consequently, sensor fusion should be based on complementary physiological information rather than simply increasing the number of predictors.

Abiotic–biotic interaction and Bulgarian context

A central implication for Bulgaria is that drought and heat should be modelled as predisposing factors rather than treated as unrelated noise. Remote-sensing studies in Bulgarian forests have already demonstrated the applicability of satellite data to bark beetle disturbance and abiotic stress (Filchev, 2012, 2020; Georgiev et al., 2022). However, mountain spruce forests differ from Central and Northern European study sites in elevation, terrain, stand structure and disturbance history. Transferability must therefore be tested rather than assumed.

For Bulgarian monitoring, the strongest design is a multi-site dataset containing healthy reference stands, documented *I. typographus* attacks and, where available, stands with fungal decay. Sentinel-2 should provide the common temporal backbone, while UAV/high-resolution data should be collected at selected plots to support crown-level reference. Climate and topographic variables should be incorporated before classification so that spectral anomalies are interpreted in their environmental context.

Research gaps and proposed framework

Three gaps are particularly important. First, many studies still use labels such as “healthy” and “damaged”, although physiological development is stage-dependent. Second, chronic internal decay is underrepresented relative to insect damage and visible crown decline. Third, reported accuracy is often based on within-site validation and therefore may not reflect transferability.

A robust research framework should consequently define four stages: (1) predisposition/physiological stress, (2) early or green attack, (3) active visible decline, and (4) post-attack mortality or chronic decay. Each stage should be represented by field observations and linked to a corresponding remote-sensing feature set. Sentinel-2 time-series anomalies should form the core regional predictor set, supplemented by red-edge/SWIR indices, climate variables and stand structure. High-resolution or UAV data should be used to refine individual-tree interpretation and validate the satellite signal. Spatially independent and cross-site validation should be mandatory.

Spatially independent validation should be treated as a methodological requirement rather than an optional improvement. Models should preferably be tested using spatially separated stands and, where sufficient data exist, across different years or study regions. Reference datasets should record not only whether a tree is affected, but also the disturbance agent, development stage, observation date and spatial unit of analysis. A resulting framework can therefore follow a hierarchical logic: first identify an abnormal physiological trajectory, then determine its disturbance stage, and finally assess the most probable biotic driver using field and environmental context. This approach reduces the risk of interpreting drought or heat stress as a specific pest or pathogen signal and provides a more transferable basis for operational forest-health monitoring.

Conclusions

Remote sensing provides a powerful means of observing biotic stress in spruce forests, but the reviewed evidence indicates that its most defensible role is the detection of physiological change and disturbance trajectories rather than direct diagnosis from a single image. Bark beetle infestation and fungal decay produce fundamentally different temporal and physiological responses: *Ips typographus* can generate detectable changes in water status, pigments and crown condition during the transition from green attack to visible decline, whereas root, butt, stem and heartwood decay may develop internally and remain weakly expressed in optical canopy data. These differences explain why temporal red-edge and SWIR information are particularly relevant for early bark beetle detection, while chronic decay requires stronger integration of structural and field-based information. No universal spectral index should therefore be expected to distinguish all forms of biotic stress.

The main methodological solution emerging from the literature is a multitemporal, stage-aware and multisource monitoring framework. Sentinel-2 time series should provide the regional backbone, complemented by red-edge/NIR/SWIR features, climate and stand variables, while UAV or high-resolution observations should be used for individual-tree assessment and targeted validation. Structural information from ALS and reliable field, harvest or pathological observations are particularly important for detecting or interpreting chronic internal decay. ML can integrate these heterogeneous predictors, but model reliability depends on representative reference data and rigorous spatially independent validation. The proposed four-stage scheme from predisposition and physiological stress, through early attack and visible decline, to mortality or chronic decay provides a more biologically meaningful alternative to binary healthy/damaged classification.

For Bulgarian spruce forests, the priority should therefore not simply be to achieve higher classification accuracy, but to develop ecologically interpretable and transferable models supported by multi-site and multi-year reference datasets. Such a system should explicitly account for the interaction between climatic predisposition and subsequent biotic disturbance and should combine Sentinel-2 observations with targeted UAV/high-resolution data, environmental information and field validation. This framework would shift remote sensing from mapping already visible damage towards earlier identification of physiological deterioration and disturbance development, while maintaining the necessary distinction between what can be detected spectrally and what requires field confirmation.

References:

1. Abdullah, H., A. K. Skidmore, R. Darvishzadeh, M. Heurich. Sentinel-2 accurately maps green-attack stage of European spruce bark beetle (Ips typographus, L.) compared with Landsat-8. Remote Sensing in Ecology and Conservation, 5(1), 2019, pp. 87–106. https://doi.org/10.1002/rse2.93
2. Allen, B., M. Dalponte, H. O. Ørka, E. Næsset, S. Puliti, R. Astrup, T. Gobakken. UAV-Based Hyperspectral Imagery for Detection of Root, Butt, and Stem Rot in Norway Spruce. Remote Sensing, 14(15), 2022, 3830. https://doi.org/10.3390/rs14153830
3. Bárta, V., P. Lukeš, L. Homolová. Early detection of bark beetle infestation in Norway spruce forests of Central Europe using Sentinel-2. International Journal of Applied Earth Observation and Geoinformation, 100, 2021, 102335. https://doi.org/10.1016/j.jag.2021.102335
4. Dalponte, M., A. J. I. Kallio, H. O. Ørka, E. Næsset, T. Gobakken. Wood Decay Detection in Norway Spruce Forests Based on Airborne Hyperspectral and ALS Data. Remote Sensing, 14(8), 2022a, 1892. https://doi.org/10.3390/rs14081892
5. Dalponte, M., Y. T. Solano-Correa, H. O. Ørka, T. Gobakken, E. Næsset. Detection of heartwood rot in Norway spruce trees with lidar and multi-temporal satellite data. International Journal of Applied Earth Observation and Geoinformation, 109, 2022b, 102790. https://doi.org/10.1016/j.jag.2022.102790
6. Ecke, S., J. Dempewolf, J. Frey, A. Schwaller, E. Endres, H.-J. Klemmt, D. Tiede, T. Seifert. UAV-Based Forest Health Monitoring: A Systematic Review. Remote Sensing, 14(13), 2022, 3205. https://doi.org/10.3390/rs14133205
7. Filchev, L. An assessment of European spruce bark beetle infestation using WorldView-2 satellite data. Proceedings of the 1st European SCGIS Conference with International Participation, 2012. https://doi.org/10.13140/2.1.3005.2647
8. Filchev, L. Application of satellite remote sensing for detection of abiotic stress in coniferous landscapes. Journal of the Bulgarian Geographical Society, 43, 2020, pp. 37–42. https://doi.org/10.3897/jbgs.2020.43.6
9. Georgiev, G. G., M. Georgieva, S. S. Dimitrov, M. B. Iliev, V. Trenkin, P. Mirchev, S. Belilov. Remote sensing assessment of the expansion of Ips typographus attacks in the Chuprene Reserve, Western Balkan Range. Forests, 13(1), 2022, 39. https://doi.org/10.3390/f13010039
10. Huo, L., H. J. Persson, E. Lindberg. Early detection of forest stress from European spruce bark beetle attack, and a new vegetation index: Normalized distance red & SWIR (NDRS). Remote Sensing of Environment, 255, 2021, 112240. https://doi.org/10.1016/j.rse.2020.112240
11. Huo, L., E. Lindberg, J. Bohlin, H. Persson. Assessing the detectability of European spruce bark beetle green attack in multispectral drone images with high spatial- and temporal resolutions. Remote Sensing of Environment, 287, 2023, 113484. https://doi.org/10.1016/j.rse.2023.113484

12. Immitzer, M., C. Atzberger. Early detection of bark beetle infestation in Norway spruce (Picea abies, L.) using WorldView-2 data. Photogrammetrie – Fernerkundung – Geoinformation, 2014(5), pp. 351–361. https://doi.org/10.1127/1432-8364/2014/0229
13. Kautz, M., J. Feurer, P. Adler. Early detection of bark beetle (Ips typographus) infestations by remote sensing – A critical review of recent research. Forest Ecology and Management, 556, 2024, 121595. https://doi.org/10.1016/j.foreco.2023.121595
14. Kędziora, W., K. Szyc, J. S. Silva, R. Wójcik. Drought and suboptimal habitats shape Norway spruce vulnerability to bark beetle outbreaks in Białowieża Forest, Poland. Land, 14(10), 2025, 2014. https://doi.org/10.3390/land14102014
15. Klouček, T., R. Modlinger, M. Zikmundová, M. Kycko, J. Komárek. Early detection of bark beetle infestation using UAV-borne multispectral imagery: A case study on the spruce forest in the Czech Republic. Frontiers in Forests and Global Change, 7, 2024, 1215734. https://doi.org/10.3389/ffgc.2024.1215734
16. Marvasti-Zadeh, S. M., D. Goodsman, N. Ray, N. Erbilgin. Early detection of bark beetle attack using remote sensing and machine learning: A review. ACM Computing Surveys, 56(4), 2023, Article 97. https://doi.org/10.1145/3625387
17. Mngadi, M., I. Germishuizen, O. Mutanga, R. Naicker, W. H. Maes, O. Odebiri, M. Schroder. A systematic review of the application of remote sensing technologies in mapping forest insect pests and diseases at a tree-level. Remote Sensing Applications: Society and Environment, 36, 2024, 101341. https://doi.org/10.1016/j.rsase.2024.101341
18. Pivovar, M., R. Näsi, E. Honkavaara, M. Blaženec, J. Škvarenina, R. Modlinger, J. Rožnovský, R. Jakuš. Spectral signatures discrimination of Norway spruce trees under experimentally induced drought and acute thermal stress using hyperspectral imaging. Forest Ecology and Management, 586, 2025, 122692. https://doi.org/10.1016/j.foreco.2025.122692
19. Räty, J., J. Breidenbach, M. Hauglin, R. Astrup. Prediction of butt rot volume in Norway spruce forest stands using harvester, remotely sensed and environmental data. International Journal of Applied Earth Observation and Geoinformation, 105, 2021, 102624. https://doi.org/10.1016/j.jag.2021.102624
20. Singh, V. V., A. Naseer, K. Mogilicherla, A. Trubin, K. Zabihi, A. Roy, R. Jakuš, N. Erbilgin. Understanding bark beetle outbreaks: exploring the impact of changing temperature regimes, droughts, forest structure, and prospects for future forest pest management. Reviews in Environmental Science and Bio/Technology, 23, 2024, pp. 257–290. https://doi.org/10.1007/s11157-024-09692-5
21. Smigaj, M., A. Agarwal, H. Bartholomeus, M. Decuyper, A. Elsherif, A. de Jonge, L. Kooistra. Thermal Infrared Remote Sensing of Stress Responses in Forest Environments: a Review of Developments, Challenges, and Opportunities. Current Forestry Reports, 10, 2024, pp. 56–76. https://doi.org/10.1007/s40725-023-00207-z
22. Stone, C., C. Mohammed. Application of Remote Sensing Technologies for Assessing Planted Forests Damaged by Insect Pests and Fungal Pathogens: a Review. Current Forestry Reports, 3, 2017, pp. 75–92. https://doi.org/10.1007/s40725-017-0056-1
23. Wulder, M. A., J. C. White, A. L. Carroll, N. C. Coops. Challenges for the operational detection of mountain pine beetle green attack with remote sensing. The Forestry Chronicle, 85(1), 2009, pp. 32–38.
24. Zarco-Tejada, P. J., A. Hornero, R. Hernández-Clemente, P. S. A. Beck. Understanding the temporal dimension of the red-edge spectral region for forest decline detection in a Mediterranean pine forest. Remote Sensing of Environment, 215, 2018, pp. 328–342. https://doi.org/10.1016/j.rse.2018.06.015