TRANSACTIONS ON AEROSPACE RESEARCH
eISSN 2545-2835, VOL. 277, NO. 34/2024, 1-13
DOI: 10.2478/tar-2024-0019

ADVANCES IN REMOTE SENSING FOR MONITORING SOIL CONDITIONS IN FOREST ECOSYSTEMS: TECHNIQUES, CHALLENGES, AND APPLICATIONS

Katarzyna Kubiak[1*] 0000-0002-4156-3139
Marcin Spiralski[1] 0000-0003-2147-2026
Joao Pompeu[2] 0000-0001-9126-8229
Vincent Levavasseur[3]
Rafał Wawer[4] 0000-0001-9266-9577

[1] Łukasiewicz Research Network – Institute of Aviation, Remote Sensing Division, Al. Krakowska 110/112, 02-256 Warsaw, Poland
[2] Basque Centre for Climate Change (BC3) – Scientific Campus of the EHU/UPV, 48940, Leioa, Spain
[3] Ver de Terre Production, 13 Chem. des Peltier, 27160 Breteuil, France
[4] Institute of Soil Science and Plant Cultivation – State Research Institute, Department of Soil Science Erosion Control and Land Protection, ul. Czartoryskich 8, 24-100 Puławy, Poland

ABSTRACT
Advances in remote sensing technologies have revolutionized the monitoring of soil conditions in forest ecosystems, providing valuable insights into soil moisture, nutrient content, and degradation without requiring physical access to remote areas. This article explores the application of key techniques, including satellite-based L-band radiometry, UAV-enabled LiDAR, and visible–NIR spectroscopy, in assessing forest soil properties. Challenges such as canopy interference, spatial resolution limitations, and data validation are discussed, alongside innovative solutions like machine learning and high-resolution digital elevation models. Case studies highlight the effectiveness of remote sensing in addressing environmental and forestry challenges, such as tracking the effects of climate change, logging, and erosion. By integrating advanced imaging technologies with ground-based observations, remote sensing supports sustainable forest management, conservation practices, and ecological research. Future developments in sensor technology, data integration, and machine learning hold promise for even greater precision and scalability in forest soil monitoring.

Keywords
remote sensing, forest soil monitoring, UAVs, LiDAR, sustainable forestry.

* Corresponding Author. Email address: katarzyna.kubiak@ilot.lukasiewicz.gov.pl
Received 23.02.2024 • Revised 13.06.2024 • Accepted 26.06.2024

INTRODUCTION

Understanding soil properties in forest ecosystems is essential for sustainable land management, conservation efforts, and ecosystem assessment. Forest managers rely on data about such soil parameters as moisture, organic carbon (important for carbon credit management), mineral deficiencies, acidification, compaction, and topography. Such data offers insights for plantation management, successful planting rates, forest dieback (due to dry season or diseases), resource estimation and inventory, and even forest fire prevention. Similar information is also required for agroforestry management, helping researchers and farmers better manage plantations.

Traditional methods of soil sampling and chemical analyses are often labor-intensive and struggle to adequately cover large or remote forested areas. Remote sensing methods provide a valuable alternative, allowing researchers and technicians to estimate various soil properties across extensive regions. Remote sensing has therefore emerged as a transformative tool for monitoring forest soils, enabling large-scale, non-invasive data collection that was previously unattainable with traditional methods. Technologies such as satellites, drones, and LiDAR provide high-resolution insights into soil parameters like moisture, nutrient content, and degradation patterns. This means that soil can be monitored over large and often difficult-to-reach areas, which is essential for both scientific research and practical applications in forestry and nature conservation.

This article examines the application of remote sensing in forest soil monitoring, with a focus on emerging techniques and their practical implications. The potential of satellite-based radiometry for soil moisture detection, the role of UAVs in capturing detailed spatial data, and the use of visible–NIR spectroscopy for soil composition analysis are explored. Despite significant advancements, challenges such as canopy interference, spatial resolution limitations, and algorithm calibration persist. This review highlights solutions, including the integration of machine learning and ground-truth data, and identifies future directions for improving the precision and scalability of remote sensing applications in forest ecosystems. By addressing these challenges, remote sensing technologies can play a pivotal role in protecting and sustainably managing forest resources.

SATELLITE REMOTE SENSING MONITORING

Remote sensing monitoring of soil moisture in forested areas was historically problematic, until the advent of microwave remote sensing. Radiometric observations in the L-band (in the frequency range of 1–2 GHz, with a sub-band centered around 1.413 GHz reserved for space and Earth sciences) have long been considered more suitable for detecting soil moisture than higher frequencies [1]. Forests, given their high vegetation density, require low-frequency observations for effective soil moisture detection. The European Space Agency (ESA) addressed this challenge by launching the Soil Moisture Ocean Salinity (SMOS) satellite in 2009, equipped with an L-band radiometer, whereas NASA launched the Soil Moisture Active Passive (SMAP) satellite in 2015 [1, 2]. These missions have brought unprecedented capabilities for observing soil moisture in forested areas from space. However, the lack of reliable reference data for soil moisture remains a major problem for quantitatively determining, developing, testing, and validating algorithms for retrieving soil moisture from satellite observations [2].

Colliander et al. [2] demonstrated that data from the SMAP satellite can be used to estimate soil moisture beneath forest canopies in temperate climates. They unequivocally showed that L-band radiometry performed in space is sensitive to soil moisture under forest canopies in these regions, although this sensitivity is constrained by the lack of representative reference data. Furthermore, Colliander et al. [3], investigated forest moisture using SMAP low-frequency data for 2019–2021, combined with radiometric observations from towers, measurement stations, and ground-based measurements. Early results indicated that the SMAP L-band measurement signal is sensitive to changes in soil moisture observed on the ground only under certain tree canopies, with an average error of about 0.05 m^3/m^3. Their study also noted that the signal permeability in the L-band is higher than conventionally assumed for forested areas, suggesting that roughly half of the emissions detected by SMAP come from the soil, and the other half from vegetation. Future research is expected to quantitatively determine spatially and temporally varying vegetation parameters to estimate soil moisture in forests on a global scale [3].

Li et al. [4] investigated the applicability of the Gaofen-1 (GF-1) satellite for modeling forest soil in two cities in Guangdong Province, southeastern China. They found that remote sensing variables reflecting vegetation status can enhance predictions of nutrient content in forest soil. The effectiveness of these remote sensing variables varied for different soil nutrients and depths. By integrating remote sensing with coarse-resolution soil maps and terrain hydrological variables, predictions of nutrient levels in the upper layers of forest soil (0–40 cm) can be significantly improved. Their study identified NDVI, a segment of the electromagnetic spectrum in the green light band, as the most effective remote sensing predictor for forest type classification. Additionally, their study area was rich in AN (nitrogen) and OM (organic matter), but had limited AP (available phosphorus) and AK (available potassium). Therefore, to enhance the condition of forests, it is essential to focus on monitoring and managing levels of AN, AP, AK, and OM.

Additionally, several studies articles have investigated the potential of satellites from the Copernicus programme, such as Sentinel-1 and Sentinel-2, for specific applications. However, most of them focus on agricultural land cover rather than forest areas. Segarna et al. [5], for example, emphasize Sentinel-2's capabilities for crop stress monitoring and its advantages over previous satellite systems, though they also note limitations and the potential need for combining field data with different remote sensing techniques.

LABORATORY SPECTROPHOTOMETER MEASUREMENTS

One of the promising methods of remote sensing soil monitoring is visible and near-infrared spectroscopy (vis-NIRS) under laboratory conditions [6]. Despite its widespread application in agricultural areas and mineral soils [7, 8], there are still few examples of its use in forest soils and organic layers. Agricultural soil monitoring involves a combination of satellite imagery, UAS technology, hyperspectral imaging, ground-based sensors, machine learning, and GIS integration. These tools and techniques empower farmers and researchers to monitor soil health more comprehensively, optimize resource allocation, and sustainably increase crop yields. Ongoing advancements in sensor technology, data analytics, and computational methods continue to enhance the effectiveness and accessibility of remote sensing solutions for agricultural applications.

In forested areas, researchers are beginning to explore the potential of vis-NIRS for soil analysis. Pietrzykowski and Chodak [9] conducted laboratory analyses of soils in post-mining sites reforested with Scots pine (*Pinus sylvestris*), demonstrating the potential of near-infrared spectroscopy (NIRS) for assessing chemical and microbiological properties. Samples from the examined sites exhibited distinct spectral characteristics, suggesting differences in the chemical composition of the organic matter within them. By using a modified partial least squares method with cross-validation, the researchers developed reliable predictive models with high correlation coefficients (≥0.90) based on NIR spectra for total nitrogen (Nt), the Corg/Nt ratio, humified carbon, humic acid carbon, and exchangeable acidity. For other soil properties (except total exchangeable bases, TEB), modeling results were considered “satisfactory” (r = 0.80–0.90). The findings emphasize the potential of NIRS for predicting certain properties of reclaimed mining soils.

Ludwig et al. [10] analyzed the applicability of spectroscopy for predicting organic carbon (SOC), nitrogen (N), and pH values, as well as enzyme activity in mineral horizons in two forested areas in Germany. Using partial least squares regression (PLSR) techniques, they demonstrated effective predictions for organic carbon and nitrogen content, but achieved more variable results for pH values, depending on the data range. Concurrently, Thomas et al. [11] investigated the use of compact MEMS (microelectrochemical systems) laboratory spectrometers for “in situ” measurements in the visible range (Hamamatsu C12880MA) and near-infrared range (NeoSpectra SWS62231). The study estimated the total C and N content in forest soil samples and compared the results with data from a conventional full-range spectrometer (400-2500 nm). The results suggest that portable MEMS spectrometers are suitable for estimating C and N content in forest soil and can contribute to improved soil monitoring in the future, given their compact size and lightweight design enabling them to be used for taking measurements both in the laboratory and "in situ".

In another study, Thomas et al. [12] evaluated the application of visible-NIRS spectroscopy to predict soil properties in forests in Saxony (Germany), with a focus on organic (Oh) and mineral (0–5 cm, Ah) horizons. The results demonstrated the usefulness of visible-NIRS in determining the C, N, C/N ratio, pH, CEC, and BS content in Oh layers, achieving R^2 values ranging from 0.44 to 0.90. In mineral layers, the results were similarly promising, with R^2 values ranging from 0.59 to 0.72. The RPIQ and RMSE values were acceptable, although they varied depending on the parameter studied. Additionally, they proposed a new perspective on mapping litter in forest soils based on pH values. The results suggest that visible-NIR spectroscopy is a useful tool for assessing litter conditions in forests, both in mineral and organic layers Oh.

Liu et al. [13] developed the Chinese Forest Soil Spectral Library (CFSSL) based on extensive soil sampling in Chinese forests, determining the soil organic carbon (SOC) content in 11,213 soil samples using visible-NIR scans. They proposed an innovative modeling method, enabling effective estimation of organic carbon content in soil on a large scale.

Gholizadeh et al. [14] assessed the potential of visible–NIR spectroscopy for classifying and predicting SOC concentrations in organic and mineral layers across 1080 forest sites in the Czech Republic. Each site had five soil levels, with Litter (L), Fermentation (F), and Humus (H) as organic layers, A1 (depth 2–10 cm) and A2 (depth 10–40 cm) as mineral layers. Using vis–NIR spectroscopy and support vector machines (SVM), the study successfully classified the soil layers based on their spectra, effectively characterizing SOC concentrations in highly variable forest soil layers in the Czech Republic. The combined organic layers model proved to be much more accurate than the combined mineral layers model (R^2 = 0.78 and R^2 = 0.53, respectively).

GEOMATIC AND REMOTE SENSING APPROACH

One common geomatic approach used to model soil conditions influenced by topography is the Topographic Wetness Index (TWI), which predicts increased soil moisture in areas with higher flow accumulation and gentler slope. However, attempts to correlate TWI with the physical and chemical properties of the soil have yielded mixed results. Generally, these correlations do match the anticipated trends, such as soil associations from ridge tops to depressions, but are mostly weak and therefore not easily generalized [15]. For instance, Case et al. [16] determined that forest soil characteristics such as soil moisture, drainage, soil type, and vegetation type are only mildly associated with TWI due to insufficient DEM resolution, complex topography, and variable soil permeability at the specific location.

Murphy et al. [15] investigated the Depth-to-Water Index (DTW), derived from LiDAR-based DEMs, to map soil and vegetation properties in a 40-ha forested area in Canada. DTW showed stronger correlations (R^2 > 60%) with variables like soil type, drainage, vegetation, and forest floor depth compared to TWI (R^2 < 25%). Soil properties such as moisture, pH, carbon, nitrogen, particle composition, and nutrient content (e.g., Ca, Mg, K, P) were better modeled using log10 (DTW) than with TWI, enabling the mapping of forest soil conditions across topographical gradients. DTW proved particularly effective for estimating local water table influences, while TWI excelled in identifying water flow and accumulation areas, suggesting that the two indices are complementary for forest soil modeling.

AERIAL REMOTE SENSING METHODS

Talbot et al. [17] demonstrated the use of Unmanned Aerial Vehicles (UAVs) to assess the impact of forest harvesting operations on soil quality. A multirotor drone equipped with an RGB (Red Green Blue) optical sensor was employed to conduct flights over six different areas after forest harvesting. Using photogrammetric techniques, they created orthomosaics that were used to identify damages caused by vehicle and machinery tracks in these various locations. Soil disturbances were categorized into three classes: light, moderate, and severe. Among the 33 hectares analyzed, 15% exhibited signs of vehicle movement, with 63% classified as light (without visible surface damage). The traffic intensity varied from 787 to 1256 meters per hectare (with a weighted average of 956 meters per hectare). The overall weighted average of damage was 4.7% of the total area, primarily due to deep ruts [17].

Nevalainen et al. [18] explored the potential of an automated method for assessing ruts created during forestry operations using autonomous drones and a proprietary approach to analyzing and processing remote sensing data. They proposed methodologies for measuring the distribution of rut depths in wood harvesting areas using photogrammetric point clouds generated by UAV-based RGB imagery. They classified ruts into two categories: slight depressions and harmful deep ruts, achieving a two-dimensional correlation (Pearson's $r = 0.67$) between manually measured rut depths and UAV photogrammetry (65% accuracy in classifying deep ruts with depths exceeding 20 cm). The two-class accuracy for detecting rut depths exceeding 20 cm was $a = 0.65$.

LiDAR IN FOREST SOIL MONITORING

Mapping terrain beneath the vegetation layer using aerial or satellite images can be challenging and often leads to inaccurate results. Conventional photogrammetric methods are unable to penetrate through tree canopies in forests, meaning that existing topographic maps of forested areas usually do not capture small-scale geomorphic details such as narrow valleys, trenches, and gullies [19]. The use of LiDAR technology with Unmanned Aerial Vehicles (UAVs) allows for remote data collection with unparalleled precision. In the case of forests, LiDAR installed on drones enables accurate scanning of the forest surface, regardless of vegetation density or tree canopies. This opens up new possibilities in the analysis and monitoring of forest soil conditions, identification of damage caused by human activities, or other factors. With LiDAR from UAVs, three-dimensional terrain models can be created, changes in terrain can be detected, and forest structure can be analyzed, which is crucial for the conservation and sustainable management of forest resources. This tool not only provides high precision but also reduces the time and cost of monitoring, making it increasingly popular among researchers and foresters involved in forest protection and management.

In the article by James et al.[20], the ability of LiDAR-ALS data to monitor erosion extent and identify channels and headwater streams in forested areas was investigated. The capability of LiDAR data to map gullies and channels in a forested landscape should improve channel network maps and topological models. On the watershed-scale, however, attempts to use LiDAR data to extract cross-sectional morphological information beneath the forest canopy ended with less success. The limited morphological accuracy of the dataset at this scale may result from the low point density on bare ground, shading of gully bottoms, and filtering of topographic inconsistencies during final processing. The ALS data used in this study are general in nature and are not suitable for detailed morphometric analysis or detecting subtle changes for gully monitoring or sediment budgeting. Data collection could be improved by targeting flights over gullies and increasing point density, through improved scanner technology or better filtering and software capabilities to distinguish between vegetation and ground surfaces.

Pierzchała et al. [19], used a multirotor UAV to generate a detailed terrain model of a mountainous area after timber extraction. They determined the dimensions, slopes, and volumes of cuts and fills associated with skidding trails. Subsequently, the acquired UAV data were compared with the before-logging terrain model from LiDAR laser scanning, and soil displacements after logging operations on a steep slope were estimated. They found UAV data to be useful as a cost-effective alternative to post-harvest studies, involving a quick assessment of disturbance extent and mapping erosion risk in various locations. Such terrain models potentially have many other applications, including hydrological and erosion modeling.

IMPACT OF IMAGE SPATIAL RESOLUTION ON SOIL MOISTURE DETECTION AND ITS IMPORTANCE

The spatial resolution of remote sensing data is a fundamental factor affecting the accuracy and effectiveness of soil moisture detection, especially in forested environments. Spatial resolution determines the smallest detail that can be distinguished in an image, influencing how precisely soil moisture levels can be mapped and analyzed. This has significant implications for forestry management, where accurate soil moisture information is crucial for making informed decisions and ensuring sustainable practices.

The spatial variability of soil moisture is influenced by the soil texture, topography (defined as slope and elevation), and vegetation, which changes over time depending on meteorological conditions such as temperature and precipitation [21]. Accurate mapping of soil moisture is essential for identifying areas with high moisture content, which can be particularly vulnerable to disturbance. For example, wet areas are more susceptible to soil compaction and rutting from logging equipment, which can damage forest floors and affect long-term forest health [22].

To address these challenges, modern forestry practices utilize advanced remote sensing technologies, including LiDAR (Light Detection and Ranging) and photogrammetry, to capture detailed topographic data. LiDAR technology, in particular, provides high-resolution point clouds that enable the creation of digital elevation models (DEMs) with finer detail and greater information content [23]. These high-resolution DEMs are crucial for accurately detecting soil moisture levels and understanding the hydrological features of forested areas.

The quality of DEMs is directly related to their spatial resolution. Higher-resolution DEMs offer improved accuracy in mapping soil moisture by providing more detailed topographic information, which is essential for identifying subtle changes in elevation and moisture patterns. DEMs are key factors influencing the extraction of hydrological features [24]. According to Murphy et al. (2009), the comparison of the performance of the DTW index and the soil moisture index (SWI) using LiDAR-based DEM (1 m resolution) and photogrammetry-based DEM (10 m resolution) showed that higher DEM resolution results in better model fit for moisture [25]. Thanks to the work of Lidberg et al. (2017, 2020), who evaluated different preprocessing methods for LiDAR DEM data with resolutions of 16 m, 8 m, 4 m, and 2 m, it is known that higher DEM resolution leads to more accurate river network extraction. In their study, river-road intersections in the DEM were compared with actual field positions [26, 27]. Mohtashami et al. (2022) confirmed that higher resolution of digital elevation models (considering 2-m, 1-m, and 0.5-m resolutions) based on high-density airborne LiDAR data does not imply improvement in identifying wet and moist areas in forest soils in relatively elevated and hilly terrain. DEM resolution of 1–2 m is therefore sufficient for planning forestry operations in similar areas where knowledge of soil hydrological features is important [28]. This level of detail allows forestry managers to plan operations more effectively, minimizing the impact on sensitive wet areas and optimizing the timing of activities to avoid soil damage.

Soil moisture maps play a significant role in both forestry and agriculture. They help identify areas of high moisture content, which is important for planning logging activities and minimizing soil disturbance. Additionally, they are useful in planning site preparation and fertilization near surface waters [29].

The Depth-to-Water (DTW) index is another DEM-based soil wetness index that calculates the least elevation difference between surface flow channels and nearby landscape areas [25]. DTW-based soil moisture maps are valuable for forestry planners in optimizing the timing of timber harvesting operations in areas with high soil moisture levels and wet soil. For instance, harvesting in winter, when the soil is frozen and can better withstand mechanical loads, helps reduce soil compaction and rutting [30]. DTW maps are also instrumental in identifying wet or marshy areas to avoid machine tracks crossing them, thereby mitigating rutting risks [31]. Leaving residues after logging on machine tracks contributes to increased soil bearing capacity in these areas before subsequent machine passes [32]. This approach is especially critical in timber harvesting near groundwater recharge areas, which have high ecological significance [33]. Although DTW maps can effectively reduce the risk of rutting near surface waters, they do not guarantee the precise location of ruts during forestry operations [34].

The spatial resolution of remote sensing data directly influences the spatial characterization of soil moisture, significantly impacting the practitioners who are the recipients of these analyses. Surface soil moisture maps identify spatial changes in moisture content within fields, providing valuable insights for farmers to quickly determine the soil moisture status and precisely allocate irrigation resources. High-resolution multispectral images enable more accurate estimation of surface soil moisture, obtainable on the day of UAV flight depending on field size and image capture count. Ultimately, this leads to much more efficient irrigation planning for farmers and irrigation managers, as they will have precise knowledge of how much water is needed in specific locations.

SUMMARY AND FUTURE DIRECTIONS FOR REMOTE SENSING IN FOREST SOIL MONITORING

In summary, remote sensing has emerged as a pivotal technology for large-scale soil monitoring, particularly in challenging forested terrains where traditional methods fall short. This technology has demonstrated significant promise in assessing various soil parameters such as moisture, erosion, organic carbon content, and nitrogen levels. Remote sensing also plays a critical role in evaluating the impact of forestry activities on soil and in mapping forest terrain. The ability to monitor these aspects non-invasively and over large areas makes remote sensing an indispensable tool in forest management and conservation. As climate change increasingly impacts forest ecosystems, remote sensing offers a vital means to monitor and adapt to these changes, supporting global conservation efforts.

The importance of remote sensing in monitoring forest soil cannot be overstated. By employing advanced techniques such as satellite imagery, aerial surveys, and unmanned aerial vehicles (UAVs), remote sensing provides valuable insights into soil quality and condition. These techniques facilitate the collection of high-resolution data that informs the modeling and prediction of soil parameters. This is particularly crucial for understanding and managing soil changes over time, which is essential for assessing the effects of logging, fires, and climate change on forest ecosystems. The technology enables ongoing observation and analysis, thus supporting both scientific research and practical forestry and conservation efforts.

Recent advancements have further enhanced the potential of remote sensing for soil monitoring. The integration of machine learning techniques has significantly increased the precision and scope of remote sensing applications. Machine learning algorithms reduce the need for extensive ground-based samples, allowing for more efficient calibration and broader assessment of soil processes. Additionally, the incorporation of Big Data analytics helps in explaining the spatial and temporal variability of soil conditions, especially as climate change impacts land ecosystems with varying intensity. However, ongoing efforts to integrate remote sensing data with ground-truth observations are also essential to refine models and enhance the reliability of predictions.

Future research should focus on several key areas to advance the field of remote sensing in forest soil monitoring. First, there is a need for continued development of higher-resolution imaging technologies to improve the accuracy of soil moisture detection. Enhanced spatial resolution is essential for more precise soil characterization and better decision-making in forest management. Second, further research should explore the integration of remote sensing data with ground-truth observations to validate and refine models. This will improve the reliability of remote sensing applications and support more accurate assessments. Third, expanding the application of machine learning and Big Data in remote sensing can provide deeper insights into soil dynamics and help address the challenges posed by ongoing climate change.

Concrete recommendations for future development include investing in next-generation remote sensing technologies, such as hyperspectral imaging and advanced radar systems, to capture more detailed soil information. Additionally, fostering interdisciplinary collaboration between remote sensing experts, soil scientists, and forestry practitioners will enhance the practical application of these technologies. By focusing on these areas, remote sensing can continue to play a critical role in sustainable forest management and environmental conservation, ultimately contributing to the preservation of valuable forest ecosystems worldwide.

ACKNOWLEDGEMENTS

This work was carried out in conjunction with the project Nature-Based Solutions for Soil Management – NBSOIL (101091246-NBSoil-HORIZON-MISS-2021-SOIL-02).

REFERENCES

[1] Colliander A, Cosh MH, Misra S, Jackson TJ, Crow WT, Powers J, et al. Comparison of high-resolution airborne soil moisture retrievals to SMAP soil moisture during the SMAP Validation Experiment 2016 (SMAPVEX16). Remote Sensing of Environment. 2019;227:137–50. https://doi.org/10.1016/j.rse.2019.04.004.

[2] Colliander A, Cosh MH, Kelly VR, Kraatz S, Bourgeau-Chavez L, Siqueira P, et al. SMAP detects soil moisture under temperate forest canopies. Geophysical Research Letters. 2020;47:e2020GL089697. DOI: 10.1029/2020GL089697.

[3] Colliander A, Cosh MH, Kelly V, Kraatz S, Bourgeau-Chavez LL, Siqueira P, et al. SMAP Validation Experiment 2019–2022 (SMAPVEX19–22): Detection of Soil Moisture Under Temperate Forest Canopy. In: IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2021). Brussels, Belgium: IEEE; 2021. p. 6992–5. DOI: 10.1109/IGARSS47720.2021.9553613.

[4] Li Y, Zhao Z, Wei S, Sun D, Yang Q, Ding X. Prediction of regional forest soil nutrients based on Gaofen-1 remote sensing data. Forests. 2021;12(11):1430. DOI: 10.3390/f12111430.

[5] Segarra J, Buchaillot ML, Araus JL, Kefauver SC. Remote sensing for precision agriculture: Sentinel-2 improved features and applications. Agronomy. 2020;10(5):641. DOI: 10.3390/agronomy10050641.

[6] Debaene G, Bartmiński P, Siłuch M. In Situ VIS-NIR spectroscopy for a basic and rapid soil investigation. Sensors. 2023;23(12):5495. https://doi.org/10.3390/s23125495.

[7] Roudier P, Hedley CB, Lobsey CR, Viscarra Rossel RA, Leroux C. Evaluation of two methods to eliminate the effect of water from soil vis–NIR spectra for predictions of organic carbon. Geoderma. 2017;296:98–107. DOI: 10.1016/j.geoderma.2017.02.014.

[8] Morellos A, Pantazi XE, Moshou D, Alexandridis TK, Whetton RL, Tziotzios G, et al. Machine learning based prediction of soil total nitrogen, organic carbon and moisture content by using VIS-NIR spectroscopy. Biosystems Engineering. 2016;152:104–16.

[9] Pietrzykowski M, Chodak M. Near infrared spectroscopy—A tool for chemical properties and organic matter assessment of afforested mine soils. Ecological Engineering. 2014;62:115–22. DOI: 10.1016/j.ecoleng.2013.10.025.

[10] Ludwig B, Vormstein S, Niebuhr J, Heinze S, Marschner B, Vohland M. Estimation accuracies of near infrared spectroscopy for general soil properties and enzyme activities for two forest sites along three transects. Geoderma. 2017;288:37–46. DOI: 10.1016/j.geoderma.2016.10.022.

[11] Thomas F, Petzold R, Becker C, Werban U. Application of low-cost MEMS spectrometers for forest topsoil properties prediction. Sensors. 2021;21(11):3927. DOI: 10.3390/s21113927.

[12] Thomas F, Petzold R, Landmark S, Mollenhauer H, Becker C, Werban U. Estimating forest soil properties for humus assessment—Is Vis-NIR the way to go? Remote Sensing. 2022;14:1368. DOI: 10.3390/rs14061368.

[13] Liu H, Wang Q, Peng J, Ji W, Li X, Viscarra Rossel RA. Development of a national VNIR soil-spectral library for soil classification and prediction of organic matter concentrations. Science China Earth Sciences. 2014;57(8):1701–10. DOI: 10.1007/s11430-013-4808-x.

[14] Gholizadeh A, Viscarra Rossel RA, Saberioon M, Boruvka L, Kratina J, Pavlu L. National-scale spectroscopic assessment of soil organic carbon in forests of the Czech Republic. Geoderma. 2021;385:114832. DOI: 10.1016/j.geoderma.2020.114832.

[15] Murphy PNC, Ogilvie J, Meng F-R, White B, Bhatti JS, Arp PA. Modelling and mapping topographic variations in forest soils at high resolution: A case study. Ecological Modelling. 2011;222(14).

[16] Case BS, Meng F, Arp PA. Digital elevation modelling of soil type and drainage within small forested catchments. Canadian Journal of Soil Science. 2005;85(1):127–37. DOI: 10.1093/forestry/cpaa010.

[17] Talbot B, Rahlf J, Astrup R. An operational UAV-based approach for stand-level assessment of soil disturbance after forest harvesting. Scandinavian Journal of Forest Research. 2018;33:387–96. DOI: 10.1080/02827581.2017.1418421.

[18] Nevalainen P, Salmivaara A, Ala-Ilomäki J, Launiainen S, Hiedanpää J, Finér L, et al. Estimating the rut depth by UAV photogrammetry. Remote Sensing. 2017;9:1279. DOI: 10.3390/rs9121279.

[19] Pierzchała M, Talbot B, Astrup R. Estimating soil displacement from timber extraction trails in steep terrain: Application of an unmanned aircraft for 3D modelling. Forests. 2014;5:1212–23. DOI: 10.3390/f5061212.

[20] James LA, Watson DG, Hansen WF. Using LiDAR data to map gullies and headwater streams under forest canopy: South Carolina, USA. CATENA. 2007;71(1):132–44. DOI: 10.1016/j.catena.2006.10.010.

[21] Lunt IA, Hubbard SS, Rubin Y. Soil moisture content estimation using ground-penetrating radar reflection data. Journal of Hydrology. 2005;307(1-4):254–69.

[22] Campbell DMH, White B, Arp PA. Modeling and mapping soil resistance to penetration and rutting using LiDAR-derived digital elevation data. Journal of Soil and Water Conservation. 2013;68(6):460–73.

[23] Wehr A, Lohr U. Airborne laser scanning—an introduction and overview. ISPRS Journal of Photogrammetry and Remote Sensing. 1999;54(2-3):68–82.

[24] MacMillan RA, Martin TC, Earle TJ, McNabb DH. Automated analysis and classification of landforms using high-resolution digital elevation data: applications and issues. Canadian Journal of Remote Sensing. 2003;29(5):592–606.

[25] Murphy PNC, Ogilvie J, Arp P. Topographic modelling of soil moisture conditions: a comparison and verification of two models. European Journal of Soil Science. 2009;60(1):94–109.

[26] Lidberg W, Nilsson M, Lundmark T, Ågren AM. Evaluating preprocessing methods of digital elevation models for hydrological modelling. Hydrological Processes. 2017;31(26):4660–8.

[27] Lidberg W, Nilsson M, Ågren A. Using machine learning to generate high-resolution wet area maps for planning forest management: A study in a boreal forest landscape. Ambio. 2020;49(2):475–86.
[28] Mohtashami S, Eliasson L, Hansson L, Willén E, Thierfelder T, Nordfjell T. Evaluating the effect of DEM resolution on performance of cartographic depth-to-water maps for planning logging operations. International Journal of Applied Earth Observation and Geoinformation. 2022;108:102728. DOI: 10.1016/j.jag.2022.102728.
[29] Ring E, Ågren A, Bergkvist I, Finér L, Johansson F, Högbom L. A guide to using wet area maps in forestry. Skogforsk arbetsrapport. 2020;1051-2020.
[30] Mattila U, Tokola T. Terrain mobility estimation using TWI and airborne gamma-ray data. Journal of Environmental Management. 2019;232:531–6.
[31] White B, Ogilvie J, Campbell DM, Hiltz D, Gauthier B, Chisholm HKH, et al. Using the cartographic depth-to-water index to locate small streams and associated wet areas across landscapes. Canadian Water Resources Journal/Revue Canadienne des Ressources Hydriques. 2012;37(4):333–47.
[32] Labelle ER, Hansson L, Högbom L, Jourgholami M, Laschi A. Strategies to mitigate the effects of soil physical disturbances caused by forest machinery: a comprehensive review. Current Forestry Reports. 2022;8(1):20–37.
[33] Kuglerová L, Hasselquist EM, Richardson JS, Sponseller RA, Kreutzweiser DP, Laudon H. Management perspectives on Aqua incognita: Connectivity and cumulative effects of small natural and artificial streams in boreal forests. Hydrological Processes. 2017;31(23):4238–44.
[34] Mohtashami S, Eliasson L, Jansson G, Sonesson J. Influence of soil type, cartographic depth-to-water, road reinforcement and traffic intensity on rut formation in logging operations: a survey study in Sweden. Silva Fennica. 2017;51(5).