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Editorial

Editorial Summary, *Remote Sensing* Special Issue “Advances in Remote Sensing for Global Forest Monitoring”

Erkki Tomppo^{1,2,*}, Guangxing Wang³, Jaan Praks¹, Ronald E. McRoberts⁴ and Lars T. Waser⁵

¹ Department of Electronics and Nanoengineering, Aalto University, P.O. Box 15500, 00076 Aalto, Finland; jaan.praks@aalto.fi

² Department of Forest Sciences, University of Helsinki, Latokartanonkaari 7, P.O. Box 27, 00014 Helsinki, Finland

³ Department of Geography and Environmental Resources, Southern Illinois University Carbondale, 1263 Lincoln Drive, Carbondale, IL 62901-6899, USA; gxwang@siu.edu

⁴ Department of Forest Resources, University of Minnesota, 1530 Cleveland Ave N, Saint Paul, MN 55108, USA; mcrob001@umn.edu

⁵ Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Zuecherstrasse 111, 8903 Birmensdorf, Switzerland; lars.waser@wsl.ch

* Correspondence: erkki.tomppo@aalto.fi

Editorial Summary

The need for timely, spatially, and thematically accurate information regarding forests is increasing because of the key role of forests in the global carbon balance and sustainable social, economic, ecological, and cultural development. While an increasing number of countries in the world already are conducting statistically sound forest inventories, a few for 100 years, inventories in other countries are still lacking, which makes the global information about forest statistics inaccurate.

The total global forest area based on the Forest Resource Assessment report of the United Nations FAO from 2020 was 4.06 billion hectares, which is 31 percent of the total land area. The rate of net forest loss declined from 7.8 million ha per year in the decade 1990–2000 to 4.7 million ha per year in 2010–2020. The net forest area loss in 2010–2020 was the largest in Africa, while the largest increases were in Asia and Europe. The world's total growing stock of trees decreased slightly, from 560 billion cubic metres in 1990 to 557 billion cubic metres in 2020, due to a net decrease in forest area while the stock per unit area increased from 132 in 1990 to 137 cubic metres per ha in 2020.

Remote sensing techniques have been utilized for National Forest Inventories (NFI) for many decades, first using mainly airborne sensors such as photography, but increasingly, space-borne sensors such as Landsat. Remotely sensed data have also been used at a global level by FAO for the purpose of comparison and as complementary information, since 1980. Some institutes have attempted to conduct global forest inventories, sometimes providing contradicting information. This implies that remote sensing-based approaches are vulnerable to misclassification and inaccurate estimation of forest parameters and changes, such as the recognition of temporarily unstocked forest areas, forest degradation, and species composition, as well as in strictly following the globally adopted definitions.

Active remote sensing technologies, such as Airborne Laser Scanning (ALS) and, in particular, Synthetic Aperture Radar (SAR), which are becoming increasingly available, provide new opportunities for large-area and global forest inventory, and sufficient repeat monitoring in a cost-efficient way. Technically and statistically sound methods are still being developed. Some gaps exist in global forest monitoring using remote sensing, such as difficulties in estimating subtle changes as well as the lack of statistically sound uncertainty estimates.

This Special Issue includes papers that attempt to overcome the gaps and describe state-of-the-art of remote sensing for forest parameter estimation and change monitoring at national, continental, or global scales.



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A short summary of the articles published is given below.

(1) Detection of Forest Windstorm Damages with Multitemporal SAR Data—A Case Study: Finland. Multitemporal Sentinel-1 data together with other geo-referenced data were used to develop methods to localize forest windstorm damages, assess their severity and estimate the total area damaged, preliminarily without new training data. The study was the first step towards an operational system for near-real-time windstorm damage monitoring. The improved k-NN method, multinomial logistic regression and support vector machine classification methods were fine-tuned and their predictions were evaluated. A method to estimate the confidence intervals of the probabilities of the predicted categories was proposed.

(2) Forest Drought Response Index (ForDRI): A New Combined Model to Monitor Forest Drought in the Eastern United States. A new forest soil drought response index (ForDRI) for long term spatial drought monitoring was developed. It uses space-borne remotely sensed data (MODIS) and other geo-referenced data. The new index identified extreme drought periods that are compatible with those calculated from forest flux-tower data. The tree ring analyses showed the impact of the drought on the tree growth.

(3) Large Uncertainty on Forest Area Change in the Early 21st Century among Widely Used Global Land Cover Datasets. The study shows large variation and inconsistency in the estimates of forest area changes that are based on the widely used global data sets and calls for the development of a more accurate database to support forest policies and contribute to global actions against climate change.

(4) A Model-Based Volume Estimator that Accounts for Both Land Cover Misclassification and Model Prediction Uncertainty. The study estimated the effects of the uncertainty of forest species maps used in sampling and on the volume estimation. The conclusions drawn were: (1) the effects of uncertainty in the forest species map on the uncertainty of large area volume estimates are not negligible; (2) overall, the effects of uncertainty in the forest species map on area estimates were greater than the effects of uncertainty in the map on the selection of field plots used to calibrate the random forest volume prediction model; (3) the effects of the forest species map uncertainty increased for open forest species or less representative forest species; (4) bootstrapping estimates demonstrated the suitability of this technique to accommodate the effects of uncertainty from more than one source; and, (5) the results are relevant for countries that use a remote sensing-based forest/non-forest map to guide the establishment of field plots.

(5) An End-to-End Deep Fusion Model for Mapping Forests at Tree Species Levels with High Spatial Resolution Satellite Imagery. A new end-to-end deep learning fusion method using high spatial resolution remote sensing images was developed by combining the advantageous properties of multi-modality representations and the powerful features of post-processing step to optimize the classification accuracy of the dominant tree species in a highly automated way. The accuracy of the method was tested for several plantation tree species in two test sites in China, such as Chinese pine and *Larix principis* in the northern test area, and Eucalyptus in the southern test area.

(6) Wide-Area Near-Real-Time Monitoring of Tropical Forest Degradation and Deforestation Using Sentinel-1. The system introduced combined time-series analysis of small objects that were identified in Sentinel-1 data, which is, segments containing linear features and apparent small-scale disturbances. A physical model was introduced for quantifying the size of small (upper-) canopy gaps. Deforestation detection was evaluated for several forest landscapes in the Amazon and Borneo. In peat swamp forests, narrow linear canopy gaps (road and canal systems) could be detected, including many gaps that are barely visible on hi-res SPOT-6/7 images. When compared to optical data, subtle degradation signals are easier to detect and they are not quickly lost over time due to fast re-vegetation. The method looks promising in recognizing relatively small changes in forest canopy cover, such as those caused by ditching or small scale logging.

(7) A Near Real-Time Method for Forest Change Detection Based on a Structural Time Series Model and the Kalman Filter. A stochastic modelling method that combines

a structural time series model with the Kalman filter was developed for near-real-time monitoring of forest changes, caused, e.g., by damages. The method was demonstrated while using Sentinel-2 data and test sites in Malawi (dry tropical forest) and Austria (temperate deciduous, coniferous, and mixed forests). The method looks promising for an automated REDD+ (Reducing Emissions from Deforestation and Forest Degradation) services in the tropics and windthrow damage assessment or bark beetle monitoring in Central Europe.

(8) Characterizing the Error and Bias of Remotely Sensed LAI Products: An Example for Tropical and Subtropical Evergreen Forests in South China. The study used nearly 8000 in situ measurements of leaf area index (LAI) from six forest environments in southern China to evaluate the magnitude, uncertainty, and dynamics of three widely used EO LAI products. The finer spatial resolution GEOV3 PROBA-V 300 m LAI product gave the most accurate LAI estimates with a multi-site dataset and captured canopy dynamics well. The MODIS 500 m product did not capture the temporal dynamics observed in situ across southern China. The uncertainties estimated for each of the EO products are substantially smaller (3–5 times) than the observed bias of the EO products when compared to the in situ measurements, showing that uncertainties are substantially underestimated and do not fully account for their total uncertainty.

(9) Analysis of the Spatial Differences in Canopy Height Models from UAV LiDAR and Photogrammetry. Six data sets, including one LiDAR data set and five photogrammetry data sets captured from an unmanned aerial vehicle (UAV), were used to estimate the forest canopy heights. Three spatial distribution descriptors, the effective cell ratio, point cloud homogeneity, and point cloud redundancy, were developed to assess the LiDAR and photogrammetry point clouds in the grid. Large negative and positive variations were observed between the LiDAR and photogrammetry canopy heights. The stratified mean difference in canopy heights gradually increased from negative to positive when the canopy heights were greater than 3 m, which means that photogrammetry tends to overestimate low canopy heights and underestimate high canopy heights.

(10) Prediction of Individual Tree Diameter and Height to Crown Base Using Nonlinear Simultaneous Regression and Airborne LiDAR Data. A compatible simultaneous equation system of diameter at breast height (DBH) and height to crown base (HCB) error-in-variable (EIV) models were developed using LiDAR-derived data and ground-measurements for 510 *Picea crassifolia* Kom. trees in northwest China. Four versatile algorithms were evaluated for their estimating efficiencies and precision for a simultaneous equation system of DBH and HCB EIV models. The simultaneous equation system could illustrate the effect of errors that are associated with the regressors on the response variables (DBH and HCB) and guaranteed the compatibility between the DBH and HCB models at an individual level.

(11) Land Use/Land Cover Mapping Using Multitemporal Sentinel-2 Imagery and Four Classification Methods—A Case Study from Dak Nong, Vietnam. A parametric classifier (logistic regression) and three non-parametric machine learning classifiers (improved k-nearest neighbors, random forests, and support vector machine) for the classification of multi-temporal Sentinel-2 images into LULC categories in Dak Nong province, Vietnam, were studied. A total of 446 images, 235 from the year 2017 and 211 from the year 2018, were pre-processed to gain high quality images for mapping LULC in the 6516 km² study area. The Sentinel 2 images were tested and classified separately for four temporal periods: (i) dry season, (ii) rainy season, (iii) the entirety of the year 2017, and (iv) the combination of dry and rainy seasons. Eleven different LULC classes were discriminated. The greatest accuracies were achieved for the composite IMG 4 obtained by combining dry and rainy season image sets while using the SVM classifier. The research showed the utility of combining Sentinel-2, multi-spectral, and dry and rainy season band data when mapping LULCs.

(12) Predicting Forest Cover in Distinct Ecosystems: The Potential of Multi-Source Sentinel-1 and -2 Data Fusion. The study investigated: (i) the ability of the individual sensors and (ii) their joint potential to delineate forest cover for study sites in two highly

varied landscapes that were located in Germany (temperate dense mixed forests) and South Africa (open Savanna woody vegetation and forest plantations). Multi-temporal Sentinel-1 and single time steps of Sentinel-2 data in combination to derive accurate forest/non-forest (FNF) information via machine-learning classifiers were used. The results indicated that optical sensors are capable of detecting homogeneous tree aggregations with high accuracies while failing at locating large portions of tree cover in open Savannas. The addition of multi-temporal microwave information to this data set showed multiple advantages. These are the correction of falsely classified cloud pixels, as well as an improved delineation of small forests in the Savanna ecosystem.

(13) Estimation of Changes of Forest Structural Attributes at Three Different Spatial Aggregation Levels in Northern California using Multitemporal LiDAR. Two modeling strategies to estimate changes in the stem volume (V), basal area (BA) and above ground biomass (AGB), of trees were developed using auxiliary information from two light detection and ranging (LiDAR) flights in the Black Mountains Experimental Forest, Northern California from two time points. The analyzed strategies consisted of (1) directly modeling the observed changes as a function of the LiDAR auxiliary information (sigma-modeling methods) and (2) modeling V, BA, and AGB at two different points in time, including a term to account for the temporal correlation, and then computing the changes as the difference between the predicted values of V, BA, and AGB for time two and time one. The predictions and measures of uncertainty at three different level of aggregation were evaluated.

(14) Remote Sensing Support for the Gain-Loss Approach for Greenhouse Gas Inventories. For tropical countries that do not have extensive ground sampling programs, such as national forest inventories, the gain-loss approach for greenhouse gas inventories is often used. With the gain-loss approach, emissions and removals are estimated as the product of activity data defined as the areas of human-caused emissions and removals and emissions factors defined as the per unit area responses of carbon stocks for those activities. Remotely sensed imagery and remote sensing-based land use and land use change maps have emerged as crucial information sources in facilitating the statistically rigorous estimation of activity data. Similarly, remote sensing-based biomass maps have been used as sources of auxiliary data for enhancing the estimates of emissions and removal factors and as sources of biomass data for remote and inaccessible regions. The current status of statistically rigorous methods for combining ground and remotely sensed data that comply with the good practice guidelines for greenhouse gas inventories of the Intergovernmental Panel on Climate Change was reviewed.

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