Forest SAT
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ABSTRACT BOOK

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Continuous Forest Inventory ‘fueling’ the adaptation of silviculture to new realities in Canada

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Introduction/Aim:
Canadian forests are facing unprecedented levels of natural disturbances. In the year 2023 alone, over 18 million hectares of forests were affected by wildfires across the country. With insect epidemics, diseases, windthrow and acute climatic events also affecting forest dynamics, Canadian silviculture is facing unprecedented uncertainty. The tools that silviculturists use are insufficient to fully inform the future growth and survival of forest stands. To provide practical solutions for silviculturists and facilitate the adaptation of their practices to new realities, industry, government and academic partners across Canada have joined forces in the NSERC Alliance Silva21 project. As part of this project, a novel continuous forest inventory framework was developed and applied across multiple forest management units, and is now ‘fueling’ the adaptation of silvicutlure to climate change.

Methods:
The framework encompasses indispensable elements for updating forest inventories, encompassing change detection and growth monitoring. Within this framework, we extend upon established applications of airborne laser scanning ALS-derived enhanced inventories, amalgamating them with data from constellations of satellites offering freely available and preprocessed moderate spatial resolution imagery for analysis. Our methodology involves fitting trajectories to sequences of pixel-level spectral index values to identify alterations. Upon detection of stand-replacing changes, pertinent values of inventory attributes at the cell level undergo recalibration and restoration in accordance with an assigned growth trajectory. Conversely, for non-stand-replacing disturbances, estimations at the cell level are adjusted based on predictive models established to correlate the observed spectral changes with relative alterations in inventory attributes.

Results:
Applications of the framework have been conducted at the Romeo Malette Forest in Ontario, Quesnel Forest in British Columbia and in Lac-St-Jean, Quebec. Results have shown that detection algorithms are efficient in the characterisation of areas affected by stand-replacing disturbances, which can help plan salvaging operations. Monitoring the variation of spectral indices over time showed that it was possible to detect non-stand replacing disturbances and quantify their impact on stand basal area. By matching spectral indices data with ring width data from dendrochronological measurements, it was possible to predict the occurrence (79.2% accuracy) and quantify the severity (R^2 = 0.70) across the landscape of a basal area growth decline observed in black spruce (*Picea mariana*) over the last decade. Such a model could be used as an early warning signal of fine-scale changes such as those due to insect defoliation or drought, and for targeted prescriptions of remedial actions such as thinning, or timely final harvest in the case of a severely declining stand. Using structural information form Aerial Laser Scanning (ALS) data, we were also able to show that the variability in growth trend across the landscape was related to forest development stage, species composition, and stand structural attributes, suggesting that these attributes could be manipulated through silviculture to produce stands that are more resistant and resilient to stressors.

Conclusion:

The near real-time information provided to silviculturists by this continuous inventory framework is providing key information that is leading the transformation of silviculture from an empirical to a more mechanistic discipline.

215

lasR: Development of an R package for Lidar Data Processing

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Introduction/Aim:

The widespread interest and adoption of ALS-based technologies in the forestry arena over the past decade have generated a need for visualisation and processing software and scripts. We present the recent development of lasR, a new R package for processing airborne lidar data and is designed as a complement of the well-established lidR package developed by the same team. The lidR package was conceived both as a toolbox and a sandbox, allowing for easy testing, exploration, manipulation, and analysis of lidar data in a research and development context within R. This vision led to several suboptimal implementation choices in terms of computing time and memory usage, such as loading lidar data into a data.frame to make them easily manipulable and compatible with other R packages. The lidR package is therefore not well suited for common tasks such as creating a digitial terrain model, a canopy height model, or biomass prediction map over large areas. In contrast, lasR has been designed to be highly efficient. Instead of a sandbox, lasR is set of well-established programs from the state of the art, carefully combined to achieve the best performances.

Results:

Unlike lidR, lasR is written 100% in C++ and does not load lidar data into a data.frame. This design allows for efficient memory management compared to the lidR package. lasR introduces a versatile pipeline engine, enabling the creation of complex processing set of consecutive stages. Users can simultaneously create a biomass prediction map and compute a digital terrain model in a single pass. The memory usage being low compared to the lidR package, it allows to parallelize the treatments on more cores. The benchmark tests show that lasR can be up to 5 times faster than lidR and use up to five time less memory.

Conclusion:

The lasR package is considerably more efficient than the established lidR package. It computes faster, can use more cores, uses less memory and allows to build more complex pipelines. The lasR package is oriented toward production, while lidR is oriented toward exploration. Both software are therefore complementary, and lasR does not supersede the lidR package.

127

A lightweight Deep Learning model for side on RGB images for near-real time, in field, hedgerow condition monitoring.

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Trees outside of woodlands are often overlooked landscape features, which deliver important ecosystem services, particularly in agricultural areas. In Northwestern Europe, hedgerows are managed linear shrub networks which have historically served as boundaries. Management of hedgerows is required to maintain their structure, but over or under management can lead to deterioration in their condition, affecting their ability to provide ecosystem services. Their ecosystem services are increasingly being valued in the market through government payments, biodiversity credits, and their contribution to net zero.

To empower farmers to monitor condition and appropriately adapt their management would often require either in-depth ecological training, or a monitoring tool to inform management decisions. In situ monitoring should be low cost, easy to use and perform rapid analysis for prompt results for uptake by land managers. Until now, hedgerow remote sensing research has been limited to aerial and satellite imaging, LiDAR and SAR data for national inventories, but has not previously assessed the potential of low-cost ground-based imaging solutions to address monitoring needs of land managers.

Here we develop a lightweight deep-learning (DL) model based on a YOLO (You Only Look Once) architecture to detect and segment stem, canopy and scale bars from side-on RGB photos of hedgerows. The model is trained on 286 images of Hawthorn (*Crataegus monogyna*) dominated hedgerow sections, the dominant species in 50% of British hedgerows, photographed at 5 locations across the Northeast of England, UK. The dataset includes images containing edge cases, including sections with other dominant hedgerow species, mostly blackthorn (*Prunus spinosa*) and ivy (*Hedera helix*), and structures including dense, frequently managed and unmanaged, to ensure a representative and broadly applicable sample.

During post processing we transform the DL model outputs into structural parameters able to act as biomass and biodiversity indicators such as height, canopy base height, stem diameters, canopy density, stem density which we evaluate against established remote sensing methods including UAV SfM, TLS and aerial LiDAR, as well as ground truth measurements. Here we present the preliminary results of the model development and discuss the operational potential.

Considering the costs, time and model size trade-offs, our lightweight field model delivers novel monitoring data to assist land managers decision making. This novel methodology could also provide a framework to engage citizen scientists to gather geo-tagged images as reference data for satellite based and other remotely sensed data.

Lidar-Measured Expressed Growth for Site Indexing

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Accurately assessing forest productivity is essential for understanding ecosystem dynamics and guiding sustainable management practices. Estimates of expressed growth and tree age at the single-tree level across a landscape can provide insights into forest function, vigor, and productivity at a finer resolution than conventional sampling methods which often are reported only as an average stand value.

Our work investigated the application of Light Detection and Ranging (LiDAR) technology to estimate single-tree productivity, expected height at fifty years, using established growth curves (Monserud 1984) and validation of implied tree ages against field age estimates (from borehole measurements) on the University of Idaho Experimental Forest (UIEF) in Moscow, ID. Estimating an expected height index from expressed growth between LiDAR height measurements provided ~1.3 million data points on the UIEF across 695 operational stands. This analysis investigated height changes across four 8-20 ppm aligned LiDAR surveys against a baseline ForestView® Digital Inventory® to calculate growth rates. A comparison of the implied tree ages to field collected increment bore age measurements suggest that estimations are well-calibrated on average. Age comparisons like these need to consider multiple sources of noise, including errors in field age estimation, growth measurements from tree peaks, and the processes applied for single-tree matching. Despite possible confounding factors such as seasonal growth variability and noise in growth measurements, our estimated single-tree expressed growth rates show spatial trends that corresponded closely with topographic and other environmental factors known to impact growth.

We believe this research demonstrates the potential of higher-resolution (>20ppm) LiDAR data to meaningfully improve the accuracy and precision of forest productivity metrics. LiDAR measurements integrated with existing growth curves provide a non-destructive estimate of site productivity that is orders of magnitude more detailed than that from conventional sampling methods.

Sensitivity of voxel size, leaf angle distribution and clumping factor in Leaf Area Density estimation in different forest types

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Introduction/Aim: Terrestrial Forest ecosystems are integral to the Earth's biosphere, significantly influencing global carbon flux through photosynthesis, transpiration, and carbon sequestration. Leaf Area Index (LAI) is a one-sided green leaf area per unit ground surface area that affects the microclimate and energy exchange. However, 2D LAI map representation cannot provide the detailed 3D spatial distribution of the leaves in a vertical profile. The location and amount of leaf area is described as Leaf Area Density (LAD), the total leaf area per unit volume, which is considered a critical parameter in radiative transfer models.

LAD estimation using direct manual methods is a time consuming and labour-intensive endeavour. An effective non-destructive alternative is Terrestrial Laser Scanning (TLS) to obtain detailed three-dimensional (3D) structural properties of forests. TLS also enables the assessment of LAD at the plot scale by measuring pulse trajectories through voxel space (a 3D spatial unit). However, the extent to which the voxel size, leaf angle distribution and foliage clumping influences the estimation of LAD in different forest types remains unclear. This issue is especially hard to solve in the real world without detailed reference data. To address this, 3D simulations of real and virtual canopies coupled with ray tracing radiative transfer models can be used to create a virtual reference to test LAD retrieval algorithms.

Methods: In this study, simulated LiDAR data using a 3D radiative transfer model (the Discrete Anisotropic Radiative Transfer (DART)) is used to analyse the sensitivity of LAD estimation arising from voxel size, leaf angle distribution, and the clumping factor. We use a novel LiDAR processing package, RayCloudTools 'RCT' combined with simulated LIDAR from a high-end commercial LiDAR system across three different forest types of Australia. The output from different sensitivity analyses is validated using this simulation approach.

Results: In previous studies, the RCT voxel method applied in vineyard leaf density estimation using a 10 cm voxel size and spherical leaf distribution has been shown to perform well. Preliminary results indicate the important trade-offs involved with voxel size and sampling density. Recommendations will be presented for how best to account for these trade-offs in a range of structural environments, including the importance of algorithm assumptions that are seldom tested (i.e. vegetation clumping within voxels).

Conclusion: This method takes advantage of ray depth penetration function of RCT and radiative transfer simulation to understand the suitable choice of voxel size, leaf angle distribution and clumping factor in three different Australian vegetation types. Sampling and voxel size recommendations will impact future data collection using this fast-growing indirect method of assessing 3D vegetation structure. Such methods can be used to benchmark remote retrievals from air- or space-borne platforms, like the GEDI spaceborne LiDAR mission.

Title: If a tree is "Protected", is it? Using satellite-borne LiDAR to understand efficacy of protection status in West African Protected Areas

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Forest integrity in West Africa faces increasing threats from human activities, such as urbanization, oil exploration, and cutting. Globally, PAs have had positive impacts on habitat protection and carbon storage, and are viewed as critical for preserving hotspots of biodiversity. However, results from a global study of biomass in PAs indicate that while the geographic coverage of PAs in Africa is comparable to other continents, biomass densities within African PAs were lower than on other continents. PAs in Africa experience high rates of disturbance from agriculture and urbanization. More research is needed to understand not only the structural makeup of PAs in this region, but also if West African PAs are more structurally diverse than their counterfactuals. To this end, this study will use the Global Ecosystem Dynamics Investigation (GEDI) lidar instrument to measure forest structure and structural diversity across West Africa. GEDI is a space-borne lidar instrument aboard the International Space Station that is capable of measuring the height and complexity of vegetation canopy. GEDI data will be processed using the Multi-Mission Algorithm and Analysis Platform (MAAP), a platform that combines data, algorithms and computational abilities for "the processing and sharing of data related to NASA's GEDI mission. We will compare forest structure metrics like Foliage Height Diversity (FHD), Canopy Copy, and Top of Canopy (RH98), as measured by GEDI, between PAs and unprotected counterfactuals. We will also derive structural diversity indices, such as Height Evenness and Beta Diversity to create an in-depth understanding of structural diversity within PAs. Finally, PA structural diversity will be examined in conjunction with PA governance type, as enforcement is a known factor in PA success. As countries expand the coverage of PAs to achieve the UN's 30x30 goal, identifying metrics for tracking PA efficacy is critical for the establishment of new PAs. To this end, we will use GEDI to examine 1) how structurally diverse PAs are in comparison to unprotected counterfactuals and 2) if areas of higher structural diversity in West Africa are indicative of higher AGB and carbon storage.

Drone Based, Multispectral Photogrammetric Point Clouds to Classify Fire Severity at Differing Canopy Height Strata

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Utilizing drone digital aerial photogrammetry (dDAP), also sometimes referred to as structure from motion, we generated three-dimensional photogrammetric point clouds to quantify the effects of fire at various canopy height strata. Our research was conducted during prescribed surface burns at Fort Jackson, South Carolina, where we collected both RGB and multispectral imagery pre- and post-fire at five plots, as well as at two control plots that were not burned. The replicate plots measured approximately 0.2 ha in size. Three-dimensional photogrammetric point clouds were generated from the multispectral and RGB imagery, and NDVI values were calculated for each point using the NIR and red reflectance values. Point clouds were normalized by removing elevation determined from airborne lidar digital terrain models and were then divided into 2-meter height stratum layers. This allowed for the comparison of point NDVI values for different canopy height strata pre- and post-fire, as well as generating orthoimages of the ground and surface vegetation only, tree canopy only, and top-down elevated view. Our results showed that the prescribed fire had a very large effect size on NDVI values up to 6 m in height, with only small effects above 6 m and within the control plots. We were also able to classify ground cover under the canopy in areas that would normally be occluded from overhead imagery, with 87% accuracy. Finally, we demonstrated that the digital removal of occluding tall vegetation increases dNDVI values and can produce a more accurate assessment of fire effects on ground and understory vegetation compared totTwo-dimensional satellite imagery that is limited to top-down (nadir) views and cannot separate understory fire effects from overstory fire effects.

Application of 3D-lacunarity derived from terrestrial LiDAR for quantification of forest structure

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Introduction/Aim: Lacunarity describes the space-filling properties or “gappiness” of fractal patterns. In forest ecology, 2-dimensional lacunarity has been used as a tool to search for structural and dynamic forest properties within and among different landscapes, and lacunarity analyses can offer insights into the spatial distribution of structural properties of forest canopies. However, while the applicability of lacunarity to voxel data, including the analysis of LiDAR point clouds, has been supported by tests with simulated data, the method has received little attention with empirical data. Here, we present a new R package ‘lacunr’, which computes 3D lacunarity for voxelized LiDAR data. We then use this package to examine changes in forest structure pre- and post-disturbance in northern California forests.

Methods: We quantified change following disturbance by hand-measuring stand density and composition in plots (400 m^2) at two sites in northern California forests before and after timber harvest (n=22) and natural wildfire (n=22). Collected metrics included basal area (BA), quadratic mean diameter (QMD), trees per plot, species per plot, and lowest live crown (LLC). We then used voxelized TLS data also collected from these plots to estimate lacunarity before and after disturbances using ‘lacunr’.

To better relate lacunarity directly to forest structure, and to use it as a proxy for forest structural heterogeneity, we conducted principal component analysis on lacunarity. The first principal component represented fine to medium scale spatial heterogeneity, and the second principal component represented large scale heterogeneity. We regressed the lacunarity-based principal components against the hand-measured stand metrics to explore how traditional forest measurement metrics are sensitive to the spatial scale of structural changes.

Results:
Significant post-disturbance changes in forest stand characteristics were observed at both sites (particularly in basal area and trees per plot). The first two principal components at the logging site accounted for ~91% of the total variance, while they accounted for ~93% of the variance at the wildfire site. Lacunarity changes were demonstrated most clearly in the first dimension of principal component analysis; both sites changed most dramatically in the fine to medium scale range (0.25m to 10m). Interestingly, this change was dependent on site, with the natural wildfire leading to increased lacunarity (i.e. greater heterogeneity) in smaller scales, and logging leading to less. Finally, the lacunarity principal components related significantly to traditional metrics, but only at the logging site. BA, LLC, and trees per plot were found to be sensitive to fine scale changes in forest structure, and QMD and LLC were found to be sensitive to large scale changes in forest structure.

Conclusion:
Understanding forest structure is integral to management strategies related to forest health and resilience, including fuel reduction, timber productivity, biodiversity and wildlife habitat. Our new approach can quantify the spatial arrangement of vegetation across scales (spatial heterogeneity) utilizing voxelized TLS data and relates to other forest structure metrics. In the future, our computationally efficient approach can be applied across larger spatial scales to further evaluate the applicability of lacunarity to assess forest structure.

Comparing Deforestation Alert Systems to Help Build Capacity to Prevent Forest Loss

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To participate in the United Nations REDD+ Initiative, countries estimate reference emissions levels from annual time-series of forest loss, gain, degradation, and other activities. While these reference levels provide valuable information on land use change and associated carbon emissions, the annual scale on which activity data is tabulated primarily allows for deforestation monitoring without the opportunity to prevent or limit deforestation events. Aiming for a more proactive approach, many countries, academics, and researchers have been working to develop and implement near-real-time deforestation alert systems that identify deforestation events within days or weeks, thereby providing enforcement authorities a chance to curtail these events.

In this presentation, I compare deforestation alerts from up to seven different alert systems at four field sites (Que Ninh, Mbaracayu, Tecpan, and Libreville) on three continents. This study tabulates the area of alert pixels within and adjacent to each deforestation site and compares the timing of alerts relative to PlanetScope daily reference data. These comparisons were conducted in the context of capacity building efforts by the U.S. Geological Survey SilvaCarbon Program which organized a series of workshops near each field site. During each workshop, in-country participants learned about the technical specifications, sensors, and relative strengths and weaknesses of each system. The purpose of these comparisons was to give in-country participants an understanding of what type of deforestation alert system might work best for them, offer insights into the complementary nature of different systems, and provide guidance on how to incorporate deforestation alert systems into national forest monitoring programs.

Afrotropic and neotropic terrestrial laser scanning data reveal that allometric AGB estimates are likely systematically biased downward by 15.3%

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Introduction/Aim:

Accurate assessment of global forest carbon stocks and changes is necessary for understanding the carbon cycle, and for informing appropriate policy and decision making towards forests, as well as channelling finance to their protection and restoration. Recent research has demonstrated that conventional methods that underpin current assessments, namely allometrics, potentially generated biased estimates, particularly in tropical forests, owing to the skewed distributions of their underlying calibration data. New methods using terrestrial laser scanning have the potential to overcome these issues, by collecting detailed 3D measurements describing entire forest scenes. However, obstructing the widespread adoption of these methods is both accurate and timely segmentation of individual tree point clouds. Here, we developed a three steps tree level AGB estimation pipeline: retrained PointNet++ model enabling woody points separation, unsupervised ML instance segmentation tuned for tropical forest, revised QSMs fitting. We applied these methods to data on thousands of trees acquired from 17 x 1 ha plots across Afrotropical and Neotropical forests. We found that these lidar-derived estimates were approximately 15% larger than allometric counterparts, suggesting that the emissions potential of the world's tropical forests is substantially different than currently thought.

Methods:

The study was conducted using high density Terrestrial Laser Scanner scans from the Peru, Gabon and Belize tropical forests: totalling to 17 ha. Firstly, an improved method for leaves removal has been developed by retraining the PointNet++ model described in Krisanski et al. (2021), with a custom tropical forest training dataset. Improved point cloud labelling method allowed better leaves, coarse wood debris and terrain removal, enabling woody points extraction. Resulting point clouds were segmented using an improved TLS2Trees (Wilkes et al., 2023) version: for each tree a path from its trunk to the branches has been found with the new set of connection rules. The algorithm has been tuned for tropical forest, ensuring tight branch connection, lianas avoidance, clear tree separation in dense canopies scenarios. For each individual tree point cloud, quantitative structural models were constructed to enable tree volume estimation, that tree species density, provided AGB estimates. Automatic segmentation results were compared to the traditional allometric equations estimates.

Results:

Semantic segmentation showed loss of 0.193 and accuracy (i.e., fraction of correct classifications) of 0.924 and 0.6691 for leaf and wood classification, respectively. Improved semantic segmentation results enabled more accurate woody points separation. Resulting point clouds were used for instance segmentation showing good results in complex forest scenes when each tree was visually inspected. Taking these segmented trees, and comparing their QSM-derived AGB with allometric counterparts, we found these lidar AGB estimates were approximately 15% greater.

Conclusion:

The biggest bottleneck for widespread adoption of terrestrial laser scanning data for forest carbon stock estimation is accurate and timely instance segmentation of individual tree-level point clouds. Supervised machine learning methods are enabling this, and providing new insights into the carbon stored in. Applying the methods we are finding that the tropical forest AGB stock likely requires a significant upward revision.

Rapid structural characterisation of tropical savanna woody vegetation with UAV-LiDAR

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Timely and spatially explicit structural assessment of the woody vegetation has been a major aspiration for earth observers and ecosystem managers. Thus far, remote sensing techniques have been unable to achieve meticulous estimations of forests within a reasonable timeframe and over ecologically meaningful areas. Advancements in Unoccupied Aerial Vehicle (UAV)-LiDAR provide high-density point clouds approaching data properties provided by terrestrial laser scanning (TLS), the current gold standard. Modern UAV-LiDAR sensors are advocated to be an appropriate solution for digital twin creation over large areas (km^2) and might be able to overcome logistical and processing constraints, providing a solution for monitoring ecosystem dynamics over time.

We tested the ability of current state-of-the-art UAV-LiDAR technology in capturing the structure of individual trees in a one-hectare tropical savanna plot in comparison to high-resolution TLS. The UAV-LiDAR data was acquired using an Acecore NOA hexacopter airframe with a Riegl VUX-120 sensor. A Riegl VZ-2000i scanner was used to collect TLS data in the same area, using a 20 m grid spacing to digitise above ground structure in rich 3D detail. After co-registering the TLS and UAV-LiDAR point-clouds, we clipped the datasets to a 1 ha plot and automatically segmented them into individual trees. We volumetrically reconstructed each tree object to access differences in wood volume estimates between the two scanning approaches. We used RayCloudTools (a new open-source C++ library) for all segmentation and reconstruction steps.

Our results showed that UAV-LiDAR could estimate total plot level tree woody volume to within 1% of the TLS estimation, and mean tree DBH and height differed by less than 3%. The UAV-LiDAR estimate of stem density was 15% lower than the TLS estimate, which can be attributed to the higher capacity of TLS in rendering understorey vegetation and producing more fully sampled stems, while UAV-LiDAR data is less sensitive to fine-scale understorey vegetation elements. Sub-plot individual tree patterns, adjusted to fit the size of GEDI footprint (25 m sub-plots), illustrated the structural heterogeneity in the area and show the potential of UAV-LiDAR for calibration of GEDI-derived data for the assessment of above ground biomass in savanna landscapes. The coupling of high-resolution UAV-LiDAR with the novel modelling capabilities of RayCloudTools provides a powerful avenue for highly detailed monitoring of ecosystems elements, and a scaling pathway for the calibration and validation of satellite-derived products.

The European Forest Information Network (EFINET): toward a forest monitoring system based on remote sensing and ground data integration

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Forests stand as a foundational ecosystem across Europe, pivotal for citizen health, human well-being, and environmental balance. They are key for both adapting to and mitigating climate change. Nevertheless, Europe currently lacks a unique and comprehensive forest monitoring system that integrates both ground-based observations and remote sensing. Presently, official statistics heavily rely on ground-based surveys conducted through national forest inventories (NFIs). While these surveys provide valuable data, they do have limitations in a pan-European context, including the relatively high costs associated with data collection, insufficient standardization efforts, infrequent updates, and often, restricted access to raw data.
As remotely sensed data become more accessible and cloud computing advances, sophisticated algorithms can now be applied over vast areas. This development creates new opportunities for producing comprehensive and updated information on forest structures and dynamics in Europe. To leverage this potential, the European Forest Institute has allocated funding for the European Forest Information Network (EFINET) project. This initiative aims to develop a prototype European forest monitoring system by integrating ground-based observations with remote sensing data.
EFINET concentrated its efforts on adapting existing methodologies and devising novel approaches within five diverse and significant study areas: Bialowieza Forest in Poland, Tuscany in Italy, the Canton of Grisons in Switzerland, the Vindelaven Juhtatdahka biosphere reserve in Sweden, and the entirety of the Netherlands. Metrics derived from Airborne Laser Scanning were utilized as reference data, given their well-established strong correlation with various forest parameters of interest. These parameters include canopy cover, diameter at breast height, tree height, basal area, biomass, growing stock volume, carbon content, and temporal changes resulting from disturbances. Subsequently, temporal patterns extracted from Landsat data were employed to establish a robust set of predictors for estimating forest three-dimensional metrics. These predictors were then utilized to produce spatially explicit estimates of forest disturbances and structural variables, complementing the estimates derived from NFIs.
Our findings demonstrate that forest height metrics can be accurately predicted through automated analysis of remotely sensed imagery, highlighting their significance within the context of a European forest monitoring system. Indeed, our approach constitutes a fundamental component of a fully integrated forest monitoring system, bridging the spatial consistency and temporal frequency of remote sensing data with the precision of ground-based observations.

Assessing urban green spaces connectivity using Copernicus data

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Introduction: With the world's population expected to reach about 10 billion in 2050, the growing trend of unregulated urbanization poses a significant threat to ecosystems and biodiversity, especially within cities. Hence, urban vegetation plays a pivotal role in maintaining not only human well-being but also ecosystem functionality against climate change and habitat degradation effects. Remote sensing is crucial for monitoring urban green spaces (UGS), with high-resolution urban vegetation cover maps supporting effective vegetation management in densely populated landscapes, where fragmentation represents a severe threat to biodiversity. Here, the spatial information provided by the European Earth Observation Programme - Copernicus - for the year 2018 was used to provide a standardized and comparable assessment of UGS and landscape connectivity at the European capital level.

Methods: First, the European Urban Vegetation Map (EUVM) was developed by implementing five Copernicus datasets (Urban Atlas, Street Tree Layer, Tree Cover Density, Grassland, Small Woody Features) in Google Earth Engine, and categorizing urban vegetation into trees, shrubs, and herbaceous types at a 10m spatial resolution for the year 2018. Utilizing EUVM data, validated against field surveys from the Land Use and Coverage Area Frame Survey (LUCAS), an ecological network model was implemented using a graph theory-based approach. Then, three global landscape connectivity metrics - Probability of Connectivity (PC), Equivalent Connected Area (ECA), and Integral Index of Connectivity (IIC) - were computed for each city. Finally, European capital cities were ranked based on relative vegetation percentage and overall landscape connectivity metrics.

Results: Validation against LUCAS showed an average overall accuracy of 83.57%. Among the cities considered, Ljubljana and Stockholm exhibited the highest proportion of vegetation within their urban cores (over 75%, primarily consisting of trees) and reported the highest overall landscape connectivity. Notably, Ljubljana recorded the highest PC (0.131) and IIC (0.098). On the other hand, Stockholm had the lowest mean distance between patches (55.12m), highest mean patch capacity (10.55 ha), and largest ECA (61269.18 ha), with a scattered patch capacity distribution (0.11 patches/ha) and a large Gini coefficient (0.96). In contrast, Valletta and Nicosia displayed the overall lowest UGS coverage and global landscape connectivity metrics.

Conclusion: The study highlights the role of Copernicus data for assessing UGS in European cities, especially due to regular updates that can be implemented for trend analysis. Also, network connectivity analysis offers relevant insights into UGS distribution, which can guide urban planning strategies to maximize ecological connectivity and halt biodiversity loss in highly anthropic landscapes such as cities. The proposed methodology supports standardized assessment at the European level, which is crucial for ensuring comparability and addressing urban sustainability and biodiversity challenges efficiently. This methodology can be also applied in different contexts and scenarios for a broader range of datasets. While this study represents an initial effort to align the understanding of UGS and their connectivity at the European level, forthcoming research should focus on investigating species-specific habitat connectivity in urban centers and standardizing additional aspects of urban landscape connectivity, such as UGS accessibility.

Estimating Forest Biodiversity, Naturalness, and Old-Growth Status: Insights from National Forest Inventory Data

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Assessing the biodiversity (B), naturalness (N), and old-growth status (OG) of forests is essential in establishing sustainable forest management plans and achieving worldwide preservation objectives. In this context, National Forest Inventories (NFIs), the official source of statistics on the status and trends of forests at the national level, may play a crucial role thanks to the wide array of variables routinely measured. Here, the study aimed to test a set of NFI-based indicators (i) able to estimate the aggregated index of B-N-OG, (ii) be supported by scientific evidence, and (iii) be assessed using data currently sampled in existing NFI datasets.

Based on a comprehensive literature review, 18 single-variable indicators were used to estimate B-N-OG indexes - normalized in a 0-1 range - from tree-level data collected in 6563 field plots during the 2005 Italian NFI. Moreover, the Copernicus High-Resolution Layer Imperviousness Degree for the year 2006 was implemented to infer the distance of NFI forest plots from anthropic disturbance. Additionally, to investigate the potential correlation between B-N-OG indexes and ecological and management conditions, the Italian network of protected areas was included in the analysis. The database was finally examined to evaluate (i) the correlations between the 18 indicators and the three indexes, (ii) geographical trends in B-N-OG indexes across Italy, (iii) the impact of the network of protected areas, and (iv) the B-N-OG distributions across different forest types and management practices.

Across the single-variable indicators, forest structure components exhibited the largest significant positive correlations with deadwood (r=0.20) and composition indicators (r=0.14), while displaying a negative correlation with regeneration indicators (r=0.16). B and OG indexes also showed the largest correlation between aggregated indexes (r=0.81). At the geographical level, the largest B-N-OG estimates occurred in mountainous regions (Trentino Alto Adige and Calabria, above all), where forests are mainly dominated by coniferous species (especially fir, spruce, beech, larch, and stone pine) that also recorded the largest B-N-OG estimates across the NFI forest categories. These findings were consistent with observations of forest management practices, wherein high forests recorded the largest B estimates, followed by uneven-aged systems, with coppices ranking last. Additionally, among Natura 2000 habitats, temperate mountain coniferous forests exhibited the largest B-N-OG estimates (0.170, 0.101, and 0.132, respectively), whereas deciduous Mediterranean forests and sclerophyllous Mediterranean forests showed the smallest estimates across all three indexes. Lastly, despite protected and unprotected areas having similar mean B estimates, statistically significant - yet small - differences in mean N and OG estimates ($p < 0.001$ and $p = 0.006$, respectively) occurred inside and outside protected areas boundaries (N= 0.07 vs. 0.05, OG= 0.09 vs. 0.08, respectively).

This study highlights the role of routinely acquired NFI data for B-N-OG assessment. By integrating additional variables beyond traditional inventory objectives, the proposed set of indicators aims for multipurpose NFI surveys. Also, the B-N-OG indexes can offer enhanced design-based assessment at the national level, supporting NFI's contribution to conservation strategies and sustainable forest management. By comparing data from different sampling campaigns, this approach could also support trend analysis over time.

Completing 3D point clouds of individual trees using deep learning

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Introduction:
In close-range lidar data collected in a forest, occlusion and increasing distance from the scanner often cause incomplete or sparse point cloud representations of individual trees, impeding accurate 3D reconstruction of tree architecture and estimation of tree height and volume.
In various other fields, point cloud completion tasks are increasingly solved by applying deep learning models [1]. However, so far, little attention has been paid to addressing gaps in 3D point clouds of natural objects such as trees using deep learning (DL) approaches.
Here, we present our findings from first experiments on fine-tuning an existing DL network to fill gaps in point cloud representations of individual trees.
We first focused on filling smaller gaps within dense point clouds of broadleaf trees, particularly in their main structures such as the stem and large branches. Currently, we focus on completing the crown shape of coarser point clouds of conifers.

Methods:
We used an existing state-of-the-art transformer-based model with an encoder-decoder architecture, which was pre-trained on diverse artificial objects [2]. Complete point clouds are required as training data, but even dense terrestrial laser scanning (TLS) datasets often contain gaps caused by occlusion. We therefore investigated the ability of point cloud completion models fine-tuned on a range of synthetic datasets to handle occlusion patterns in real-world point clouds. We explored whether simple cylinder tree models or more naturalistic 3D meshes are sufficient as training data and tested the benefit of using simulated lidar scan patterns as input for fine-tuning the model [3]. To test the models, we used independent real-world TLS data.

Results and Conclusion:
Using a limited number of real and synthetic broadleaf trees, we successfully fine-tuned a general pre-trained completion model to close holes in the surface of branches and to fill gaps between unconnected branch parts, while retaining their organic shape. Our findings indicate that fine-tuning a network on synthetic tree data can enhance the model's ability to complete tree objects compared to a general model trained on diverse artificial objects. Generally, 3D point cloud completion with DL has shown the potential to enhance point clouds of individual trees, thus facilitating further steps in the processing and analysis of 3D forest data.

Outlook:
In dense conifer stands, occlusion commonly occurs at the treetops in TLS scans or at the lower stem portions in UAVLS scans. Unlike deciduous trees, detailed reconstruction with cylinders is less common for conifers. Instead, there is greater interest in assessing stem volume and overall crown shape [4]. Consequently, our current focus lies on completing the crown shape and height of coarse point clouds of individual conifers, particularly those with missing treetops. To achieve this, we use an international collection of segmented individual tree point clouds derived from TLS and UAVLS data sources.

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New unsupervised Bayesian methodology for timely detection of forest loss in the Brazilian Amazon and cerrado woodland savanna using Sentinel-1 time series data

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Forests worldwide have undergone significant transformations due to forest loss [7], highlighting the critical need for real-time forest monitoring to prevent further vegetation loss and facilitate prompt interventions. Traditionally, forest loss monitoring relied on optical imagery [3], which is obstructed by its susceptibility to cloud coverage, especially in tropical regions. In recent times, Synthetic Aperture Radar (SAR)-based systems have emerged to enable all-weather operability [2], [5], [6]. However, SAR-based approaches encounter challenges, such as the alterations in backscatter caused by factors like soil moisture variations. Moreover, accurately detecting small-scale disturbances remains problematic for SAR systems, partly due to the spatial filtering techniques employed to mitigate the effects of speckle. Additionally, monitoring forest loss in regions characterized by pronounced seasonality in backscatter signals, such as dry forests and savannas, poses limitations, resulting in substantial under-monitoring of these extensive carbon sinks.

This study introduces an unsupervised SAR-based method for detecting forest loss, employing Bayesian inference through an infinite state Markov chain. The approach treats forest loss as a change-point detection problem within a Radiometrically Terrain Corrected (RTC) Sentinel-1 single polarization time series. Notably, this method preserves the native resolution of measurements without resorting to spatial filtering. Each new observation contributes to the probability of deforestation occurrence, leveraging prior information and a robust data model [1]. The method's sequential adaptation process ensures resilience against variations and trends, facilitating forest loss monitoring not only in dense forests but also in areas influenced by seasonal changes.

In evaluating the proposed method, tests were conducted by comparing different configurations, representing varying levels of conservatism, to existing Near Real-Time (NRT) forest loss monitoring systems, including GLAD-L [3], RADD [6], and combined Global Forest Watch (GFW) alerts during the observation year 2020. In particular, GFW includes alerts from GLAD-L, GLAD-S2, and RADD where available. The assessment focused on small validation polygons (i.e., <1ha) in both the Brazilian Amazon and the Cerrado woodland savanna. The performance metrics such as detections, omissions and false alarms were calculated in comparison to the MapBiomas Alerta validation dataset [4].

Our research unveiled significant progress in detecting small-scale disturbances, accompanied by a remarkable reduction in false alarms across the examined biomes. In the Brazilian Amazon, our method achieved an F1-score of 97.3%, surpassing the 93.1% obtained by the current best-performing NRT system. Furthermore, a focused comparison underscored the existing systems' tendency to overestimate forest loss, likely due to spatial filtering impacting data resolution. In contrast, our method demonstrated more precise detections in absence of filtering and significantly lower false alarm rates in comparison to all considered systems, regardless of the configuration. In the Cerrado, our approach attained an F1-score of 97.4%, distinctly surpassing the 75.5% obtained through leading optical technology. In conclusion, our adaptive approach significantly improved forest loss detection with low false alarm rates, demonstrating efficacy in both the extensively monitored Amazon, and the Cerrado, where seasonal changes pose challenges to existing systems, leading to limitations or the absence of monitoring.

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High Accuracy Mapping of Peatland Typologies, Distribution and C Stocks via Dense Time Series of Optical and Radar Imagery

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Peatlands represent a strategic belowground carbon pool that occurs on merely 3-5% of the land surface, but represents the largest C store of the terrestrial biosphere. Since peatlands represent a C storage and sequestration pool that can most readily be conserved and restored, the United Nations recently completed a Global Peatland Assessment for increasing awareness of preserving and restoring peatlands as a strategy to help mitigate climate change. However, there is a data gap in our current knowledge of the geospatial distribution, type and extent of C rich peatlands across the globe. The ability to accurately map peatland types and monitor their extent, impacts and condition has been a focus of study by several researchers and governments. Using a combination of optical and microwave sensors from multiple seasons within a given subregion has been shown to allow for the characterization of peatland typologies from boreal, temperate, and tropical ecoregions. There are limitations in accuracy for mapping at global scales using a single approach due to the rich diversity of forested and non-forested peatland typologies that occur across the globe. Therefore, the approach needs to be tuned to the region of interest. Challenges of peatland mapping include limited field data, high cloud cover in many regions of interest, and radiometric differences between adjacent mosaicked images due to variable environmental conditions. These issues can be overcome to a great degree with the increasing availability of dense temporal datasets from Sentinel-1, Sentinel-2, Landsat, NISAR, etc. These datasets combined with cloud computing is allowing for broader areas to be mapped with limited field datasets. Cloud computing and dense temporal data allows for temporal normalization, and in the case of SAR temporal speckle filtering, for improved mapping capability.

We have examples of high accuracy peatland maps and in situ soil C measures that have allowed for improved accounting of C-storage estimates from the Peruvian Amazon, Andean mountains, and boreal Northwest Territories. Cloud based approaches and new tools utilizing the dense time series data are demonstrated in de novo mapping of the western United States Rocky Mountains, where sparse networks of mountain fens occur, and in coastal mangrove and inland areas of the Democratic Republic of Congo.

Accurate mapping of peatland typologies and extent with high resolution (<30 m) sensors linked with field data are necessary to reduce uncertainties in estimates of the distribution of C stocks, but also to allow for decisions to prevent and mitigate threats from land use and climate change. The most efficient way to move forward with mapping and monitoring at regional and global scales is using dense time series datasets in cloud environments. Further, remote sensing based on a combination of microwave and optical sensors has been shown to aid in monitoring peatland degradation, C flux and soil C emissions from wildfire. Knowledge of where peatlands are on the landscape and understanding their role in global C cycling, and thereby their importance to climate mitigation, gives decision makers tools and information to implement policy for peatland protection, conservation, restoration and sustainable use.

Mapping Global Forest Cover of the Year 2020 to Support the EU Regulation on Deforestation-free Supply Chains

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On 9 June 2023, the European Commission published the EU regulation for deforestation-free supply chains aiming to reduce EU's impact on global deforestation and forest degradation (*EU 2023*). This regulation lays down rules for seven commodities (cattle, cocoa, coffee, oil palm, rubber, soya, wood) and associated products. A forest/non-forest map corresponding to the cut-off date (31 of December 2020) could serve operators in the assessment of risk of deforestation when declaring land parcels by geolocation for commodities and products imported to or exported from the European Union market. Although several global maps providing tree cover information are available at different scales, the transformation of tree cover, representing the state of the land as observed by Earth Observation systems, to "forest" as defined under a land use concept requires additional data. Not all trees correspond to the definition of forests (e.g. agriculture tree plantations or urban use) and not all forests have trees, e.g., temporally unstocked forest.

We present a harmonized and globally consistent map of forest cover (GFC) presence/absence for the year 2020 at 10m spatial resolution (*Bourgoin et al. 2024*). First, we assimilated many freely available global data layers of tree cover and then excluded areas that do not meet the forest definition.

Experts who reviewed the work found the map to be an appropriate spatial representation of forest cover with no major large-scale mapping errors. Dense forests and forest edges in structured landscapes were found to be correctly mapped and delineated. More challenging areas such as dry forest lands, ecotones and complex landscapes with mosaics of degraded forest and agricultural plantations are prone to more frequent mapping errors. GFC 2020 may show some errors when compared to regional or national maps for specific commodities addressed under the regulation, notably for cocoa and coffee and in specific areas for rubber (overlaps between GFC2020 forest class and maps of commodities). Meanwhile comparisons with regional maps for oil palm, soy and pasture (as surrogate for cattle) show satisfactory results (no or limited overlaps). The preliminary overall accuracy of the map using a validation sample set of forest management types (*Lesiv et al. 2022*) is estimated at 76% with higher omission than commission errors.

This map will play a supporting role in the implementation of the EU Regulation on deforestation-free supply chains but has no authoritative status. For due diligence, it is recommended to use it with other forest or land use maps and complementary datasets, particularly at national scale, if existing and available. We envision an improved version of the map before the Regulation becomes applicable by the end of 2024 along with a statistically and thematically robust accuracy assessment.

Quantifying the Magnitude and Persistence of Human Degradation of Global Tropical moist Forests using Landsat and GEDI data

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Tropical forest degradation from selective logging, fire, and edge effects is a major driver of carbon and biodiversity loss (Pearson et al. 2017; Baccini et al. 2017; Barlow et al. 2016). The rate of degradation is comparable to that of deforestation and exceeds it during extreme climatic events (Vancutsem et al. 2021). However, the actual extent of degradation impacts is likely underestimated, and large uncertainties remain in quantifying its persistence at global tropical scale (Gao et al. 2020).

We quantify the magnitude and persistence of multiple types of degradation on forest structure over the pantropical belt by combining Landsat-based wall-to-wall maps of forest degradation, deforestation and regrowth from 1990 to 2022 (Vancutsem et al. 2021) with spatially discontinuous estimates of canopy height and biomass from spaceborne LIDAR (GEDI, Dubayah et al. 2020) from 2019-2022.

Based on more than 40 million sample footprints of GEDI data, we estimate that forest height decreases due to selective logging and fire by 15 and 50 % respectively, with low rates of recovery even after 20 years. Agriculture and road expansion trigger a 20-30% reduction in canopy height and biomass at the forest edge, with persistent impacts measurable up to 1.5 km inside the forest. Edge effects encroach on 18% (~206 Mha) of the remaining tropical moist forests, an area more than 200% larger than previously estimated (Brinck et al. 2017). Finally, degraded forests with more than 50% canopy loss are significantly more vulnerable to subsequent deforestation.

Taken together, our findings call for greater efforts to prevent degradation and protect already degraded forests to meet the conservation pledges made at the recent United Nations Climate Change and Biodiversity conferences.

Early detection of Bark Beetles by Drone Images differs in Endemic and Epidemic Populations

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European forests face increasing threats due to climate change-induced stressors, which create the perfect conditions for bark beetle outbreaks. The most important spruce forest pest in Europe is the European Spruce Bark Beetle (*Ips typographus* L.). Effective forest management of these beetles' outbreaks necessitates the timely detection of recently attacked spruce trees, which is challenging given the difficulty in spotting symptoms on infested tree crowns. Population density is one of many factors that can affect infestation rate and symptoms development. This study compares the appearance of early symptoms in endemic and epidemic bark beetle populations using high-resolution UAV (Unmanned Aerial Vehicle) multispectral imagery.

In spring of 2022, host colonization by bark beetles was induced on groups of spruce trees growing in 10 sites in the Southern Alps, characterized by different population density (5 epidemic and 5 endemic). A multispectral sensor mounted on a drone captured images once every two weeks, from May to August 2022. The analyses of a set of vegetational indices allowed the actual infested trees' reflectance features and symptoms appearance to be observed at each site, comparing them with those of unattacked trees.

Results show that high bark beetles population density triggers a more rapid and intense response regarding the emergence of symptoms. Infested trees were detected at least one month before symptoms became evident to the human eye (red phase) in epidemic sites, while this was not possible in endemic sites. Key performing vegetation indices included NDVI (Normalized Difference Vegetation Index), SAVI (Soil Adjust Vegetation Index, with a correction factor of 0.44), and NDRE (Normalized Difference Red Edge index).

This remote early-detection approach could make a great contribution to the development of tools for the automatic diagnosis of bark beetles' infestations and provide useful guidance for the management of areas suffering pest outbreaks.

A Sub-meter Canopy Height map of the Earth generated by a Foundational Vision Transformer

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Vegetation structure mapping is critical for understanding the global carbon cycle and monitoring nature-based approaches to climate adaptation and mitigation. Assessments of tree canopy height and crown projected area at a high spatial resolution are also important for monitoring carbon fluxes and assessing tree-based land uses, since forest structures can be highly spatially heterogeneous. Very high resolution satellite imagery makes it possible to extract information at the tree level while allowing monitoring at a very large scale. This presentation presents a global, 0.5 meter canopy height map of the planet for 2020. The maps are generated by the extraction of features from a self-supervised model trained on Maxar imagery, and the training of a dense prediction decoder against aerial lidar maps and observations from GEDI. The presentation summarizes the scaling of our teams prior work on subnational canopy height mapping to the rest of the planet, and will discuss engineering and model challenges and successes for large-scale training and inference of vision transformer models for high resolution imagery.

Development of Annual Ten-meter Tree cover Loss and Gain Data

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Several methods and datasets for mapping forest disturbances, such as deforestation and tree cover loss due to natural causes, exist based on dense optical or radar time series. Mapping tree cover gain, either due to regrowth following disturbance, tree planting, or longer term vegetation transition, is relatively less well understood. This oral presentation will introduce 10-meter annual maps of tree cover loss, gain, and rotation under development from 2017 onwards. This work utilizes annual tree cover maps generated by applying a supervised convolutional neural network classifier to Sentinel-1 and Sentinel-2 imagery, and conducting post-classification change detection via kernel density estimates of the Sentinel-2 time series. The oral presentation will summarize the applications of the Tropical Tree Cover data on Global Forest Watch, and present emerging use cases of annualized data for tracking forest and landscape restoration progress.

130

Characterizing Community Fire Risk from Satellite Data and Multi-Temporal Lidar

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Rural communities in the west of Canada are exposed annually to a risk of wildfires. Assessing wildfire risks in advance allows communities to undertake mitigation actions such as prescribing fuel treatments. In this study, LiDAR data in combination with satellite is used to perform advanced fire risk assessment by generating fuel types and characterizing fire hazard at different spatial scales. Fuel attributes key to managing fire behaviour, including Canopy Bulk Density, Canopy Fuel Load, Stem Density, Canopy Base Height, and Canopy Height, were estimated using area based and individual tree-based techniques on LiDAR data at 5, 10 and 20m2 resolutions. An individual tree inventory (ITI) derived from the LiDAR provided the tree segmentation and was the data aggregated to the 3 different resolutions. Next, attributes such as Stem Density, Canopy height, Canopy Base Height, ladder fuel density, and vegetation types were computed based on 2014 and 2020 data. Fuel type data based on the ITI and Sentinel-2 Satellite were assessed using existing field plots. Using these outputs, several different fire models based on the generated fuel type data and fuel attributes were produced using Canadian Forest Fire Danger Rating System models. Finally, risk estimates derived from these fire models were generated for all buildings in the community based on radiation and ember density exposure, as well as proximity to other structures. The results show that a much more detailed map of fuel attributes and fuel types can be generated using LiDAR and satellite with R2 of 0.74 for lidar fuel types vs. an R2 of 0.56 for traditional inventory polygon approach. These maps can be used to identify structures with the highest wildfire hazard exposure as well forest areas containing the most hazardous fuel structures. Fuel management prescriptions can then be generated to target specific areas identified, enabling better use of funds to enhance the safety of the community

Detecting non-stand replacing disturbances in a near-real time context using Landsat and Harmonized Landsat Sentinel-2 time series

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Introduction:
Non-stand replacing disturbances (NSRs) are events that do not result in complete removal of trees and generally occur at a low intensity over an extended period of time (e.g., insect infestation, drought), or at spatially variable intensities over short time intervals (e.g., windthrow, partial burn, frost). These variable disturbance intensities and spatial patterns often lead to heterogenous stand structures and changes to the quality and quantity of biomass, thereby impacting timber supply and ecosystem services. Conventional inventory methods for monitoring NSRs are often conducted as part of annual aerial surveys which can be insufficient in both temporal and spatial resolution for managers tasked with adaptive decision making.

The increased accessibility of moderate spatial resolution satellite imagery with frequent temporal revisit (e.g., 2-3 day return interval for Harmonized Landsat Sentinel-2; HLS) has seen an increase in algorithms designed to detect sub-annual change in forested landscapes over large spatial scales. One such algorithm, the Bayesian Estimator of Abrupt change, Seasonal change, and Trend (BEAST) has shown promise with sub-annual change detection in temperate environments, with > 88 % detection of disturbances when compared to a validation data set.

Methods:
Here we evaluate the sensitivity of BEAST to detect NSRs across a range of disturbance agents and severity levels in British Columbia (BC), Canada from 2002- 2020. To do so, Landsat (2000-2016; 2000-2001 was used to spin up the algorithm) and HLS (2016- 2020) data were used to create a time series of 16-day normalized burn ratio (NBR) composites for an area of 1.4 M-ha. This time series data was utilized by BEAST to produce rasters representing the change probability, which were then compared to the occurrence, severity, and timing of disturbances as mapped by the BC annual aerial overview survey (AOS). Differences in the distributions of BEAST probabilities between agents and levels of severity were then compared to undisturbed stands.

Results:
Results indicate that when compared to undisturbed stands, the BEAST disturbance probabilities were on average higher and statistically different ($p < 0.05$) for the most prevalent insect disturbances within the region (i.e., Mountain Pine Beetle, Aspen Leaf Miner, Spruce Beetle amongst others) in addition to abiotic disturbances (i.e., non-biological injuries, fire, windthrow, avalanche and snowslides, landslides, aspen decline, and cedar flagging). When assessed across different AOS defined severities, BEAST probabilities were on average higher and statistically different in 6 of the 6 years where very severe disturbance was observed, and in 15 of the 19 years where severe disturbance was observed. Lower-severity NSR events were less well discriminated from undisturbed stands.

Conclusion:
The sensitivity of BEAST change probabilities to a wide range of NSR disturbance agents at varying intensities suggests promising opportunities for earlier detection of NSRs to inform continuously updating forest inventories. And with this enhanced detection new possibilities for adaptation and mitigation tactics to be implemented.

Assessing spatio-temporal disturbance in Australian softwood plantations with multi-resolution satellite sensors.

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Current methods in Australia for detection of poorly performing softwood plantations range from irregular ground inspection, through annual expert observations from helicopter or aircraft to occasional use of spaceborne multi-spectral sensors. The cost of aerial observations over large extents is substantial. However, regular image acquisitions from satellites provide the potential for more timely and cheaper assessments of plantation condition.

The aim of this nationally funded two-year research project is to assess the cost effectiveness of using differing resolution multi-spectral satellite sensors to detect symptoms of plantation disturbance.

The geographical focus for this project is a large section of southeastern and eastern Australia covering approximately 370,000 ha of non-contiguous pines. Whilst species vary slightly from *Pinus radiata* to *P. elliottii*, the climate, topography, damage agents and silvicultural management practices vary substantially across the study area.

Satellites sensors of differing resolutions have been selected. These are Sentinel 2 (10-20-60m), PlanetScope (3m), SkySAT (2m) and Pleiades Neo (1.24m). The latter two satellites are pan-sharpened to 0.5m and 0.3m respectively. Using cloud computing, the Forest Disturbance Index (FDI) using Tasselled Cap Coefficients (TCC) (at ground reflectance) for six of the Sentinel 2 bands, is applied to seasonal geo-medians. Processing is restricted to plantation estates using GIS supplied by foresters. Atypical FDI values both spatially and temporally (seasonally and annually) are detected using statistics. Atypical pixels are compared with ground truth established at six 10km x 10km sites where high spatial resolution aerial CIR imagery is captured. Machine learning (ML), using extensive training from forest experts, is applied to this imagery to detect disturbed individual trees. In addition, near simultaneous PlanetScope and Pleiades Neo imagery is captured, analysed and compared with the ground truth.

Ground truth was successfully established from ML applied to aerial imagery and enabled the health of individual crowns to be classified. When pan-sharpened Pleiades Neo satellite imagery using standard spectral indices is compared with ground truth, individual infected trees can be detected with variable accuracy. However, gaps in the forest canopy lead to false positives. Currently we are developing a non-canopy mask to reduce these errors. At the lower resolution of Sentinel 2, the application of the spatio-temporal FDI shows that individual discoloured/infected trees cannot be detected. When atypical trees cluster at three or more, FDI can detect them. Again, gaps in the forest canopy lead to false positives; we are currently trialling two methods to remove these effects. Additionally, we are currently experimenting with the derivation of species specific TCC for all 11 Sentinel 2 bands. This should provide increased sensitivity in unhealthy tree detection.

Whilst this project is 50% complete, early findings demonstrate that Sentinel 2 imagery can be processed over large extents, at low cost, to detect plantation disturbance. This is not successful at the individual tree level. As the resolution of the satellite sensor increases, as does the cost, unhealthy individual trees are able to be detected. Finding the optimum balance between resolution and cost is the challenge that this research will answer by June 2025.

Virtual forests and unsupervised domain adaptation for training deep learning-based models for tree analysis from LiDAR point clouds

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Deep learning algorithms have recently achieved state-of-the-art performance in tasks such as individual tree classification, part segmentation and tree analysis using 3D LiDAR point cloud data of forests. One of the main downsides of deploying supervised deep learning is the need for extensive training datasets, i.e. LiDAR point clouds that have been annotated for target tasks (e.g. tree part labels) by human experts, that are used to train models that can process new, unseen data. One strategy for addressing this issue, which has shown success in applications outside of forests, is the use of simulated synthetic data (with automatically generated annotations) for training deep learning models which are deployed on real target data/environments.

In this talk, we explore and evaluate the use of biologically-accurate virtual forest stands (including simulated tree growth/structure and simulated LiDAR scanning processes) to be used to train deep learning models for analysing trees for LiDAR point clouds. We have developed a high-fidelity tree simulation pipeline which simulates a variety of different tree structures and scanning processes which can be used to generate large datasets of synthetic trees with automatically annotated per-tree attributes, without the need for human expert annotation. We develop deep learning models for tree part segmentation and estimation of tree parameters such as stem diameters, stem volume and branching structure which are then trained using our synthetic tree data. We have also developed a unsupervised domain adaptation method which uses un-labelled, real LiDAR data from the target environment to fine-tune the model, which is then deployed on real LiDAR datasets.

Results of our approach are shown across high and medium resolution LiDAR captures from both mobile terrestrial and airborne laser scanning of several plantation forest environments in Australia and New Zealand (resolutions ranging from 300-8000 points per m^2). We compare performance metrics for tasks such as tree part segmentation when models are trained using synthetic data vs. real LiDAR datasets. Our results show that models trained on our synthetic data pipeline can outperform models trained on real LiDAR data, in particular when real data-trained models only have access to training data from non-target sites. We also demonstrate that the use of unsupervised domain adaptation methods further improves the accuracy of synthetically-trained models.

Outcomes of our study have implications for reducing the burden required in manual human expert annotation of large LiDAR datasets required to achieve high-performance from deep learning methods for forest analysis. The use of synthetically-trained models shown here provides a potential way to reduce the barriers to the use of deep learning in large-scale forest analysis, with implications to applications ranging from forest inventories to scaling-up in-situ forest phenotyping.

Sentinel-2 and EnMAP-based analysis of a Red Needle Cast Outbreak in New Zealand

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Introduction/Aim:

Radiata Pine (*Pinus radiata* D. Don) is the most planted conifer globally and in New Zealand. Red Needle Cast (RNC) is one of several diseases that threaten the species [1]. After some smaller outbreaks in the previous years, a severe outbreak happened in 2023 in the Gisborne region of New Zealand's North Island.

We use Sentinel-2 time series to document the areal extent, the severity, and the starting date of the outbreaks of 2021 to 2023. Furthermore, EnMAP hyperspectral data is used to characterize the spectra of damaged stands depending on the severity and the age of the infection.

Methods:

Analysis-ready Sentinel-2 data of the study area were processed using FORCE [2], including download, geometric and atmospheric correction, cloud masking, resampling of all bands to 10 m spatial resolution and tiling the data into a regular grid. We calculated pixel-wise mean values of the chlorophyll-sensitive Red-Edge Chlorophyll Index (CIre) spanning the years 2017 to 2021 for each month.

As an alternative method to pinpoint the first occurrence of RNC in a stand, instead of calculating monthly means we fitted a harmonic series consisting of three sine functions to the 2017 to 2021 time series of several indices at each radiata pine pixel: an index that uses a continuum removal of the SWIR water absorption, the CIre, and the tasseled cap greenness. This series was extrapolated and for each Sentinel-2 scene the difference between expected and measured index value was calculated. Differences larger than two standard deviations and a minimum threshold were flagged as disturbance.

Thirdly, EnMAP data recorded at four dates between November 2023 and February 2024 were analyzed to characterize spectral reflectance of radiata pine stands without RNC expression and at different number of months after RNC expression was first detected.

Results:

Differences from the respective monthly mean value gave a good indication of RNC damage. Maximum RNC expression occurred in September 2023. CIre differences were significant starting March 2023, so pre-visual detection was possible using Sentinel-2 time series. The detection accuracy will be tested on more than 2,200 points for each year from 2019 to 2023.

Detection of RNC based on extrapolated harmonic series also gave very plausible results that will be validated using the same reference points. The best spectral index for characterizing RNC damage is still to be determined.

Recovery after RNC infection or lack thereof will be documented using EnMAP and Sentinel-2 data. First results hint at recovery after about one year after mild outbreaks, but since the 2023 outbreak was more severe than previous ones the coming months will show whether the trees are able to recover.

Conclusion:

Satellite remote sensing can be used for pre-visual detection of RNC over large areas. Several strategies will be tested and compared in order to find a possible operational strategy for an early warning system. Multispectral and hyperspectral data both can play a crucial role in understanding spread of RNC and recovery or die-off after the first detection.

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RapidFEM4D: A web-based mapping platform for assessing the impacts and near-term recovery of Hurricane Ian on forest ecosystems in Florida

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Introduction/Aim: The catastrophic effects of hurricanes on forest ecosystems underscore the need for monitoring tools that can assess and predict the ecological aftermath of such natural disasters. Hurricane Ian, which swept through Florida, left behind a trail of destruction that highlighted this need. In response, our aim was to develop and offer an open-source web-based mapping platform that provides a temporal sequence of hurricane disturbance severity and recovery maps across forested areas within hurricane Ian's path in Florida.

Methods: Spaceborne lidar, synthetic aperture radar, and passive optical data were used as input for a Random Forest model to quantify aboveground biomass density. This data enabled us to generate wall-to-wall maps that provided a detailed visual representation of the biomass density across the affected regions. We then conducted a thorough assessment of the pre- and post-hurricane biomass estimates to assess the severity of the damage inflicted by the hurricane Ian. Furthermore, we overlaid biomass loss maps with geographic information on Florida counties, yielding estimates of hurricane-induced biomass damage at the county level. Finally, output maps were hosted on the RapidFEM4D platform, an open-source, web-based mapping platform designed to enhance the accessibility and applicability of our research.

Results: The RapidFEM4D, accessible via http://rapidfem4d.silvalab-uf.com/, facilitated the creation and dissemination of detailed maps that display variations in aboveground biomass density before and after the hurricane's Ian passage. Visual assessments conducted using these maps have highlighted significant changes across different forest areas and at the county level. Users can analyse specific areas of interest by utilizing the platform's tools to derive estimates of biomass loss and damage severity. This feature significantly enhances the platform's utility, as it allows for a more personalized examination of the hurricane's effects. Initial user feedback indicates that the ability to quantify damage at both a broad scale and a more granular, county-level perspective is highly valuable for targeted response and recovery planning.

Conclusion: The RapidFEM4D stands as an important tool for stakeholders, academia, and decision-makers, in the context of hurricane impact assessment on forest ecosystems. This accessibility facilitates informed decision-making and fosters collaborative efforts towards sustainable forest management and disaster mitigation. By providing open access to crucial data and analytics, RapidFEM4D enhances our collective ability to respond to and recover from natural disasters, supporting a broad spectrum of users in developing targeted strategies for resilience and conservation.

Exploring Ecuador's Mangrove Forests: Mapping and Monitoring with the MANGLEE Tool

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Introduction/Aim:

Mangrove ecosystems maintain ecological equilibrium and support the socioeconomic welfare of coastal communities. Renowned for them, these ecosystems are highly productive and provide a wide range of ecosystem services, including provisioning of resources, coastal protection, and fostering social and cultural connections. Despite mangroves are facing a concerning decline worldwide, their cover continues to decrease due to land use transformations into urban, agricultural, and aquaculture exploitation. To safeguard mangroves, various restoration and conservation programs have been initiated, albeit with varying degrees of success. However, the lack of control and monitoring by local authorities, particularly in developing countries, are among the reasons for the dilution or failure of those programs. Remote sensing technology offers an effective means to track changes in mangroves, with recent advancements enhancing mapping efficiency and cost-effectiveness. Nonetheless, the implementation of remote sensing techniques is often limited in developing countries due to economic, administrative, and technical factors. To address this problem, our aim has been to develop an accessible, intuitive and multi-purpose tool, MANGLEE (Mangrove Mapping and Monitoring Tool in Google Earth Engine), that leverages remote sensing data and machine learning to facilitate sustainable mangrove management.

Methods:

MANGLEE comprises three independent modules. The first module prepared Synthetic Aperture Radar (SAR) and optical data from Sentinel missions, creating a SAR and optical composites and calculates SAR and spectral indices. Module two integrated SAR and optical composites, makes a supervised classification based on the Random Forest algorithm to obtain binary maps of Mangrove – Non-Mangrove and calculates the measure of accuracy in the results. Finally, module three detects the changes and catalogues them into degradation or improvement. Considering user interaction, each module is a notebook connected to Google’s Collab and available in Git Hub. The performance of MANGLEE was tested in the mangroves of Guayas, Ecuador, region historically threatened by shrimp farming. We analyzed changes over two time periods 2018-2020 and 2020-2022. Additionally, to ensure the use of the tool, we held training sessions for local staff.

Results and Conclusion:

The practical application of MANGLEE tool has unveiled a concerning trend: despite legal protections, mangrove-covered areas in Guayas continue to experience deforestation processes. Our analysis indicates a substantial loss exceeding 2900 hectares. The primary drivers behind this loss are the expansion of infrastructure and the maintenance of the aquaculture industry. These findings underscore the pivotal role of MANGLEE in effectively monitoring mangrove ecosystems, even in the face of challenges such as cloud cover. Furthermore, local training becomes the perfect medium for disseminating results, including both tool usage and coverage maps, serving as key tools for sustainable mangrove management.

Towards satellite product validation using multi-scale lidar

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Introduction:
Forests around the globe are experiencing significant changes in their structure and species composition due to human land use and global climate change. Essential Biodiversity and Climate Variables (EBVs/ECVs) provide a quantitative basis for monitoring these changes through space and time, and to evaluate the effectiveness of conservation and management strategies. However, the tools currently available for large-scale ecosystem monitoring, particularly from space, are not specifically designed for detailed vegetation observation, and they lack the spatial and temporal resolution needed to capture the full three-dimensional structure of vegetation and vegetation change at local scales.

The challenges in monitoring forest dynamics related to (up)scaling are twofold: first, the impact of dynamics on forest structure at local levels and, second, the detection and monitoring of dynamics or disturbances globally using satellite data. Traditional ground-based plots, while offering precise 3D structural data through terrestrial laser scanning (TLS), are limited by their size and the frequency of data collection. This makes them less ideal for satellite calibration and validation (cal/val) in the context of forest dynamics monitoring.

Aim/Methods:
To bridge this gap, multi-scale laser scanning aims to enhance reference data for validating spaceborne measurements. Multi-scale laser scanning can be across spatial or temporal scales, or both.

Results:
This presentation highlights the benefits of multi-scale laser scanning through findings from two distinct projects: one across spatial scales and one across temporal scales. The first project involves a network of permanent tropical forest plots in Australia, analysed using both terrestrial and UAV laser scanning (UAV-LS). This study spans a range of rainfall and altitude conditions and compares data collected in 2018 and 2024 to assess biomass dynamics. Our results affirm the effectiveness of TLS in accurately capturing key structural tree metrics at the plot scale and the use of UAV-LS in quickly and accurately measuring canopy tree structures across larger landscapes. The fusion (i.e. combined datasets) of TLS and UAV-LS data is not crucial for individual tree measurements but primarily serves as a means to upscale stand-alone UAV-LS structural measurements at the landscape-scale.

The second project introduces an automated permanent laser scanning network across six supersites in Germany and Belgium. This setup, utilising high-temporal-resolution (daily) scanning, moves beyond the limitations of conventional TLS methods, allowing for continuous monitoring of ecosystem structure and its correlation with ecosystem functioning, specifically microclimate dynamics or phenology. Equipped with LEAF automated laser scanners and microclimate loggers, these supersites provide valuable insights and practical considerations into daily and seasonal variations in plant area volume density and the effect on local ecosystem processes.

Conclusion:
Multi-scale laser scanning is important in providing objective, accurate, and precise in situ reference measurements in support of conservation and management strategies across spatial and temporal scales. Initiatives like GEO-TREES stand to benefit significantly from advancements in multi-scale laser scanning, offering high-accuracy reference data for satellite-based biomass mapping. Moreover, the development of automated monitoring networks (e.g. StrucNet) is essential for generating the calibration data needed by satellite missions to effectively monitor vegetation structural dynamics over extensive areas.

Differentiating eucalypt tree species and provenances using UAV hyperspectral imagery and machine learning

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Understanding the genetic composition of natural and restored ecosystems is increasingly necessary for the effective management of biodiversity and ecosystem health in the face of global change. In the case of forests, trees are a foundation component of that biodiversity. The identification of tree genotypes to the species and provenance levels is increasingly important for the evaluation of the success of different seed-sourcing strategies aimed at climate change adaptation and resilience. Popular methods to achieve this, including pedigree tracking or molecular techniques, can be costly and in some cases prohibitively expensive. In this study, we explore the possibilities offered by advances in very high-resolution hyperspectral imagery, acquired from Unmanned Aerial Vehicle (UAV), to differentiate between species and provenances based on their unique spectral signatures.

Using a common garden restoration experiment, random forest classifiers were trained to discriminate between: (a) two focal eucalypt species (*Eucalyptus pauciflora* and *E. tenuiramis*); (b) *E. pauciflora* provenances from Tasmania and mainland Australia ('state'); and (c) ten different Tasmanian provenances of *E. pauciflora* ('provenance'). We compared both object- (*i.e.,* tree) and pixel-based approaches; using the spectral information directly or as derived vegetation indices, both with and without 3D structural traits derived from Light Detection and Ranging (LiDAR).

Species were best classified when using he fusion of derived vegetation indices and LiDAR at the object-level, with an overall test accuracy (OA) of 87.6%. However, the object-level models performed poorly when differentiating the spectral differences between state (OA = 56.7%) and provenances (OA = 28.6%), with vegetation indices and the fusion of vegetation indices and LiDAR being the top models, respectively. While there was little gain in detectability of species at the pixel-level (OA = 88.1%), substantial gains were achieved in differentiating intraspecific spectral differences at the state (OA = 82.4%) and provenance (OA = 50.4%) levels. Employing a mixed odds-ratio and majority vote approach on the pixel affinities for each object, we were able to increase our ability to differentiate objects at all hierarchical levels: species (100% correct classification); state (92%); and provenance (95%).

We discuss the results within the context of applying these methods to broadscale monitoring of tree biodiversity at spatial- and genetic-scales relevant to natural resource managers.

Quantitative characterization of needs and preferences of end users for the generation of tree list maps to project forest management scenarios under climate change conditions in Spain

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Introduction/Aim:

The European Union (EU) Forest Strategy for 2030 identify the most important threats for forests (e.g. forest fires or climate change) and establish the guidelines and objectives shaping forest management practices in the coming years. It is of vital importance to provide forest managers with tools to anticipate potential consequences of competing management alternatives, e.g. distance-independent climate-sensitive tree-level growth models (DI-CS-TLGM) and fire spread simulators. These models are available for most forest types in Spain but require input data in the form of tree lists maps that have not been developed yet. Nowadays, plenty of open remote sensing (RS) data and ground observations in forest environments are available in Spain to develop tree list maps. However, the high level of disaggregation of this output requires considering the main preferences of the final users of these RS products.

We propose a replicable methodology to integrate available sources of information into predictive models to generate tree list maps to satisfy the information needs of forest managers. This methodology adapts the one developed in Meddens et al. (2022) to the Spanish context and it is preliminary based in interactive sessions where land managers are asked about their most important needs of information, the precision requirements that they have and the spatial detail at which they develop their work. This information is used to inform the selection of models for tree list prediction.

Methods:

The characterization of needs and preferences is organized in two tasks. The first one focused on contacting groups of potential users and delivering a questionnaire to identify most important responses for management applications. For this purpose, we contacted five different group users of tree list maps (e.g. forest managers from public administration, private forestland owners, firefighting personnel, scientists from universities and research centers, and professionals from private companies). We used the methodology described in Meddens et al. (2022) for the identification of needs about RS products. The interviewees were asked to enumerate variables verifying that can be computed using data from Spanish National Forest Inventory (SNFI) plots, and if available in a map format would facilitate their work. In the second task, interactive sessions will be implemented to collect answers to Analytic Hierarchy Process (AHP) questionnaires to obtain preferential weights for the variables identified in the previous task. The answers will be used to derive preferential weights that will be used in the model fitting stage.

Results:

Preliminary results highlighted the importance of having aggregated products such as total volume or basal area, but also the need for more disaggregated information such as diameter distributions. Interviewees consistently reported difficulties in data access and data maintenance, despite the availability of numerous open datasets. The respondents also identified difficulties or lack of technical expertise. The results of this survey are important for the generation of tree list maps. Adhering to the needs reported by final users we will be able to generate products that will enable using tools for creating a more diverse and resilient forest structures.

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A comparison of very-high resolution satellite imagery products for assessments of urban green and open space: A case study of two urbanizing African cities

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Introduction/Aim:
Urban green and open space (UGOS) plays a critical role in the mitigation of adverse urbanization effects and provision of social and ecosystem services. Global sustainable development initiatives and local management efforts seek to evaluate the status of UGOS to understand broader relationships between UGOS and urbanization, inform the distribution of anticipated UGOS developments, and maintain or improve the accessibility and quality of existing UGOS. UGOS can be effectively monitored over large spatial and temporal extents using very-high resolution (VHR) Earth Observation data (<=10m), image processing, and spatial analysis. While a variety of VHR satellite imagery options exist, the spatial coverage and resolution of the data can vary, and access to higher resolution imagery may be constrained by monetary costs or access restrictions. Comparing the capabilities of differing VHR imagery for mapping UGOS related land cover may inform more accurate assessments of UGOS.
Objective and Methods:
We contrast spatial evaluations of UGOS in two urbanizing cities, Mekelle, Ethiopia and Polokwane, South Africa, utilizing land cover maps produced from VHR satellite imagery of varying accessibility, coverage, and spatial resolution. The imagery we classified and evaluated included 10-meter Sentinel-2 imagery, 3-meter Planet imagery, 2-m Maxar imagery, and pansharpened 0.5-m Maxar imagery. Following land cover classifications, we examined composition of undeveloped versus developed land, detection of tall vegetation, and access to public open space according to Sustainable Development Goal Indicator 11.7.1.
Results:
Our examination of developed versus undeveloped land across the VHR products revealed negligible differences in Mekelle, but significant differences in Polokwane, likely due to variations in land cover heterogeneity. According to landscape metrics, tall vegetation was better detected under higher resolution imagery across both cities but displayed different patterns in each city. Our assessments of public open space access were influenced by the differing input imagery and has implications for future spatial assessments of SDG 11.7.1.
Conclusion:
Overall, our work highlights the potential limitations of accessible, coarser VHR imagery in UGOS land cover analyses but further illustrates its value in work that will promote global sustainable development and improve urban vitality in resource limited regions.

Incorporating Model and Reference Uncertainty into Accurate Assessments: A proposed generalization of current best practices

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Accurate and precise estimates of land-use and land cover (LULC) are critical for making wise management decisions. Probability sampling designs are statistically robust strategies for working with accuracy assessment data of LULC classifications, to produce bias-adjusted estimates of omission/commission error and class area. While today's state of the art has excellent statistical treatment of errors, it does not yet fully incorporate the important aspect of variation in confidence within a study area. From both the perspective of a given LULC model and of reference data, the label at any given point may well be less than 100% certain. For example, imagine a setting where the LULC model estimates that a given plot is 63% likely to have been deforested; meanwhile, 3 of 4 independent interpreters called it deforested. Considering the potentially large impact on accuracy and area estimates of incorrectly labeled information, how could the uncertainties at that point be considered when estimating the overall accuracy of the classes and map, in a way that respects and builds on the careful work that forms the state of the art?

Here we propose an approach to treating varying confidence when making estimates from LULC classifications. It is designed to consider both model uncertainty and reference uncertainty in weighting a reference data point for an accuracy assessment. Thinking of each reference and/or model as being a vector of LULC probabilities at each sample point, we use a dominance measure to assign a confidence-driven weight. Scores range from unity, meaning perfectly certain it is a given class, to 0, representing complete uncertainty about a point. The resulting contingency table is analyzed using "effective points", where uncertain points are valued as less powerful than those with higher-confidence labels. Once the power of each point is weighed, estimates of area can proceed using the established calculations to produce bias-adjusted values.

The resulting calculations have several appealing characteristics. First, they produce reasonable differentiation among points with different confidence. Points of low confidence are able to be neither trusted completely nor discarded as though they had no value. Second, points of different weights are combined into a familiar contingency table. Third, the method is agnostic to how uncertainties are determined, allowing users to define uncertainties in whatever way is best for a given project. Fourth, when there is 100% confidence in both the model and reference data, the calculations give the same result as current best practices.

In addition to explaining this generalization, we provide a working code repository that can be used in accuracy assessment estimation. Test data includes working examples of typical use cases with data from some best-practices research. By proposing a straightforward way to integrate uncertainty in reference and/or model data, we see this work as a step toward accuracy assessments that more fully reflect real settings where fair estimates are needed that weigh multiple data sources. We encourage others to try it out and work with us to evaluate the usefulness and robustness of this approach.

Using terrestrial LiDAR to examine the effect of understory fuels management on forest heterogeneity in a northern California mixed hardwood forest

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Introduction/Aim:
Measuring forest structure after disturbance is integral to assessing forest health, wildlife habitat, and future wildfire behavior. Terrestrial LiDAR (TLS) can capture accurate and fine-scale stand measurements from which forest structural diversity metrics can be derived—including measures of canopy height, vegetation arrangement, canopy cover, structural complexity and leaf density. These TLS-derived metrics provide an opportunity for more objective quantification of forest structure which have been otherwise costly, time-consuming, or impractical to measure traditionally. For example, surface and ladder fuels, which are difficult to measure in the field, can have profound effects on localized fire behavior, as branches and leaves are considered fuel, but are often distributed in a heterogeneous way under the canopy. While ladder fuels can be indirectly measured using canopy base height, the vertical and horizontal distribution of the understory is often not described. One metric that could be used to characterize this distribution is lacunarity, a scale-dependent measurement of spatial heterogeneity. However, 3D lacunarity has not been widely estimated using TLS data due to the computational time investment of previous analysis approaches. Our study aims to quantify changes in sub-canopy forest structural heterogeneity with a focus on changes in fuel connectivity following understory fuels management after a natural wildfire.

Methods:
We collected TLS data from 20 plots representing several forest types in a northern Californian mixed hardwood forest before and after a low to moderate severity wildfire and post-fire understory fuels thinning treatment. Using voxelized TLS data and a newly developed R package “lacunr”, we calculated 3D lacunarity of all vegetation (dead and alive) under 8 meters to represent ladder and surface fuels.

Results/Conclusion:
Preliminary results show significant changes in lacunarity following both wildfire and post-fire thinning with a greater increase observed after understory thinning. This suggests that while wildfire can alter the distribution of understory fuels, the specific management approach used in these plots to reduce understory fuels <10 cm in diameter more effectively altered the arrangement of fuels and reduced connectivity. Importantly, our results support using 3D lacunarity calculated from LiDAR data as a metric to objectively quantify changes in the arrangement of fuels post-disturbance and evaluate management strategies.

Monitoring Forest Management Activities with High Spatial and Temporal Resolution using Multispectral VTOL UAS

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Introduction/Aim:
The importance of harmonizing long-term environmental ground-data to facilitate comparisons within and between ecosystems at different scales is widespread consensus (Haase et al., 2018). However, the costs of maintaining such monitoring are considerable (Zhang et al., 2016), which raises the question of the convenience and reproducibility of ground-based surveys at larger scales. In this sense, drone-based remote sensing has the potential to bridge the gap between ground-based surveys and satellite remote sensing platforms (Guerra-Hernández., 2021, Ecke et al., 2024). In the last years, this field has experienced an exponential development and improvement (Pajares et. al., 2015, Librán-Embid et al., 2020), especially in the field of forestry. However, despite their potential, there is still a lack of comprehensive research on understanding the advantages and the drawbacks of a UAS-based monitoring for forest management activities. This study seeks to address this gap by evaluating the capabilities and limitations of a vertical take-off and landing (VTOL) aircraft equipped with a multispectral camera set-up, focusing on assessing the imagery processing efforts and its performance in spatio-temporal forest monitoring at different levels landscape to individual trees in comparison with ground-truth data.

Methods:
This study took place in the Julius-Maximilians-University Forest in Sailershausen, Central Germany, covering approximatelly 270 hectares. The Uncrewed Aerial Vehicle employed for this study was a WingtraGENII fixed-wing drone equipped with a Micasense Altum camera capable of capturing images across red, green, blue, red edge, near-infrared, and thermal bands. Geometric corrections were performed using fifteen ground sample points established during each visit and measured with an RTK GNSS receiver with precision of up to 1 cm. The field data acquisition took place between the 8th of February and the 22nd of November 2023 with an avergage interval of 1.5 weeks between datasets for a total of 21 visits.

To process the datasets, we employ a standard structure-from-motion processing pipeline, for creating digital surface models and orthomosaics. Following the processing of individual flights, we conduct mosaic stitching, dataset co-registration, and base grid sampling. Utilizing the homogenized outcome datasets, we perform single tree detection and crown delineation to extract multitemporal crown spectral statistics, for plots of different management practices. Subsequently, we compare this information with ground truth data provided by the Sailershausen Forest Office, which includes diameter at breast height and information on the species composition as well as management practices. Finally, we conduct spectral resampling to evaluate plot treatment discrimination at different synthetic resolutions.

Expected Results:
From these processes, we expect to obtain a detailed characterization of the spatio-temporal dynamics from forest metrics at individual trees and landscape levels which proves the capabilities of VTOL-UAS. Additionally, we analyze how this methodology adds value to current monitoring schemes by evaluation its cost effectiveness including the downsides of this technology (e.g. data quality impact of different weather conditions), and we describe how they should be addressed to build a relative systematic monitoring system that includes both UAV and space-borne remote sensing as well as ground truth data.

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Artificial Intelligence on Aerial Imagery (AI2) for individual tree inventory in mixed boreal forests: is it better to work on the individual drone photos or the orthomosaic?

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Introduction/Aim: Drones and artificial intelligence (AI) are increasingly used for enhanced forest inventories that provide information on every tree in a stand required for precision forestry. Here we demonstrate and compare two possible workflows that start with either individual drone photos or an orthomosaic derived from them, and end in a geospatial census of trees, namely a GIS layer consisting of points representing individual trees with attributes such as species, height, crown diameter and others such stem volume that could be derived from published allometric equations. We also introduce a new, open projection code for transferring annotations to a GIS, and discuss pros and cons of each workflow and the factors affecting accuracy.

Methods: We initially used a YOLOv8 (a popular AI model) trained, validated and tested (60/20/20 % split) on ~10k bounding boxes corresponding to tree crowns of five classes (pine, spruce, poplar, larch and dead trees) from ~150 manually annotated drone true color (RGB) images of ~1cm GSD from an 8 ha mixedwood stand in the boreal plains of Alberta, Canada. The trained YOLOv8 was applied to images acquired by the same system (a DJI M300RTK with a Zenmuse P1 camera) over the same stand in a different date. The detected boxes were projected onto an orthomosaic derived from those same photos based on the position, aim, internal parameters (focal length and radial and tangential distortion) of the camera, plus its distance to the treetop of the corresponding box (obtained from ray tracing). Duplicate detections of the same tree coming from different photos were removed using an ad hoc non-maxima suppression (NMS). The result was manually revised as to create a new reference dataset with ~ 16k trees that was used to train another YOLOv8 model, this time based on the orthomosaic rather than the original drone photos. Two versions of the orthomosaic-based model were tested, the conventional RGB, and another where the blue channel was replaced by a Canopy Height Model (CHM) derived from the photogrammetric point cloud.

Results: The model trained on the original drone images achieved precision, recall and mean average precision at an IoU threshold of 50% (MAP50) of 0.60, 0.67 and 0.65, respectively. The same accuracy metrics for the model trained on GIS-projected, refined boxes were 0.63, 0.64, and 0.64, respectively. At the class level, the F1 score ranged from 0.84 for pine, the most common tree in the stand, to 0.44 for larch, the least common tree which is easily confused with spruce. The modified orthomosaic that included a CHM did not lead to better results.

Conclusion: Both workflows (applying the AI to the original drone images vs. the orthomosaic) seem to lead to similar results. However, the analysis of reference ground data, which will be completed before the summer, may provide additional insights. Working on the original drone images has the advantage that they are free from artifacts common in orthomosaics derived from Structure from Motion (SfM). However, it requires precisely aligned images and camera calibration parameters.

PhenChile: advances on the Chilean National Phenological Monitoring System

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Monitoring changes in leaf phenology using remote sensing is one of the simplest and most efficient way to detect and geographically assess the effects of climate change on vegetation. Global warming is altering the Earth vegetation phenological cycles, being the most evident symptom the timing shift of the onset, offset and growing season length. Regional to continental shifts in phenological timing can modify large scale biogeographical patterns affecting biodiversity, forest production, pest dynamics, agriculture and food availability. Several national and international efforts have been made to develop operational remote sensing based phenological monitoring system as well as ground observation networks of time-lapse cameras or “Phenocams”. Particularly in Chile, a 4,000 km long country, an alliance between the Pontificia Universidad Católica de Valparaíso, the National Forest Service Conaf and the Ministery of Environment have developed a land-surface-phenological monitoring and anomaly detection system. The web-platform is based on remote sensing vegetation indices and a flexible non-parametric probabilistic algorithm (the “npphen” R package) capable to reconstruct any type of annual leaf phenology using remote sensing data and to quantify its inter-annual variation by means of percentiles from the reference frequency distribution (RFD). Negative phenological anomalies with RFD > 0.95 trigger a “red alert” which is displayed on the web application as soon as the satellite data become available. Furthermore, a Phenocam network is under construction with daily RGB photos taken from ten sites (and in expansion) and transmitted via wireless to the central server. In this work, we introduce the web application http://phenchile.pucv.cl/, launched in March 2024, along with preliminary results and a discussion of future opportunities and challenges.

Immersive Visualisation of Dense Point Cloud Data in Forest Inventory

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Introduction/Aim:
Forestry management relies on accurate and efficient assessment of tree populations.
In this study, we explore innovative approaches to enhance forest inventory using immersive visualisation (Virtual Reality - VR) and machine learning techniques. Our primary aim is to develop operational methods and workflows that empower forest professionals to make informed decisions based on dense point cloud data.

Methods:
Our research introduces a novel **human-in-the-loop framework** that integrates a human-operated VR immersive environment with machine learning-based automated individual tree measurements. This framework empowers operators to assess high-density point cloud tree data effectively. We conducted two user experiments to evaluate the impact of tree visualisation and assess the design of the human-in-the-loop framework. Here’s how the human-in-the-loop framework works:

Immersive VR Environment: Operators step into a virtual forest, where they can explore and interact with 3D representations of trees. The immersive experience allows them to assess individual trees more intuitively.

Machine Learning for Tree Measurements: We employ machine learning algorithms to automatically extract critical tree parameters from dense point cloud data such as stem diameter.

Human Assessment: Operators review the automated measurements and provide feedback. Their expertise ensures accuracy and refines the assessment and system.

Results:
Our research yields several key findings:

Potential of Immersive VR: The initial usability test demonstrates that immersive visualisation significantly impacts the accuracy of virtual tree assessments. Operators can visualise complex forest structures more effectively, leading to improved inventory outcomes.

Challenges in Framework Design: The second usability test highlights the need for careful design. Balancing user interaction, machine learning algorithms, and real-world forest conditions poses challenges. We discuss strategies for overcoming these hurdles

Conclusion:
This research sheds light on both the promise and obstacles of introducing a new forest inventory practice—virtual inventory using VR technology and machine learning. By bridging human expertise with cutting-edge machine learning algorithms, we can revolutionise how we assess and manage our forests.

Assessing forest structural complexity: insights from alternative laser scanning approaches

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Forest structural complexity describes the size, shape and spatial arrangement of vegetation, being valuable information for forest management and conservation. Structural complexity can be estimated with conventional measurements, but to increase the level of detail, estimation accuracy and scalability, numerous remote sensing techniques have been developed. In this study we utilized close-range airborne and terrestrial laser scanning (ALS, TLS) to understand how well these technologies capture vertical, horizontal and volumetric complexity of the forest. Our goal was to generate new insights for forest structural complexity assessment to address whether additional value is obtained from TLS measurements conducted on-site, or if assessments from ALS point clouds suffice. Additionally, we investigated whether structural complexity should be assessed directly as the variability in the sampled observations (grid-level approach) or through the variability of the dimensions of individual trees (object-based approach).

Research was conducted in boreal forests in Southern Finland. TLS and ALS data were collected in May 2021 from 99 circular plots with a radius of 20 m. ALS data was collected from a helicopter at an altitude of 80 m, resulting in point cloud density of 1 800 pts/m^2. TLS point clouds were acquired using one center scan and eight auxiliary scans from plot borders, with one scan featuring 3 mm point spacing at 10 m distance. Using the ALS and TLS point clouds, we computed metrics characterizing vertical, horizontal, and volumetric forest structural complexity using both grid and object level approaches. At the grid level, estimations included canopy height model variability and canopy cover variability within 6 x 60° sectors, as well as the proportion of voxels filled by vegetation, measuring vertical, horizontal, and volumetric complexity, respectively. Object level estimations were based on individual tree detection and characterization of the variability in tree height (vertical), crown area (horizontal), and box-dimensions (volumetric complexity). To assess which method could capture the largest variability in complexity, we applied F-test to compare ranges of the complexity measures between ALS and TLS. Agreement between ALS and TLS-based structural complexity estimates were assessed using coefficient of determination (R^2) and Spearman's rank correlation coefficient.

ALS captured a wider range of vertical complexity through the object-level approach, but TLS demonstrated greater capability in characterizing the range of horizontal complexity. TLS was also capable of capturing a significantly wider range of volumetric structural complexity estimations compared to ALS ($p < 0.05$). In general, object-level estimations had a broader range in both horizontal and vertical complexity ($p < 0.05$), whereas grid-level estimations obtained a significantly larger range in volumetric complexity. The highest agreement between the ALS and TLS was recorded for tree crown height ($R^2 = 0.66$, Spearman rank = 0.76), whereas the lowest agreement was found for box-dimension ($R^2 = 0.03$, Spearman rank = 0.25).

The results of this study highlight that object level estimations can capture a broader range in variation, and therefore these approaches should be prioritized in structural complexity assessments. However, grid-level estimation with TLS provided better characterization of the range for volumetric structural complexity.

Landsat Next: Temporal, Spatial and Spectral Improvements Leading to Scientific Discovery and Decision-Making During the Next Half-Century

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During 2022, the Earth observing community celebrated both the 50th anniversary of Landsat 1 and the initiation of “Landsat Next”, the follow-on mission to Landsat 9. The Landsat Program has established itself as the cornerstone of a growing constellation of Earth observing imagers due to its broad applicability; global coverage and management-scale resolution; rigorous geometric and radiometric calibration; long-term continuity of measurements; and free access to more than 10 million Earth images. Furthermore, powerful synergies exist when Landsat data are combined with similar 2D surface reflectance data (e.g., Harmonized Landsat Sentinel-2, HLS) and 3D lidar sensing products (e.g., ICESAT-2, GEDI), especially for forestry-related applications. Landsat Next will continue the Landsat legacy using a constellation of three identical observatories and new imaging technology to deliver two to three times the temporal, spatial and spectral resolution of any previous Landsat mission (6d revisit for 26 bands; 10 to 20m VSWIR and 60m atmospheric/TIR). Landsat Next’s measurements will enhance and improve forest management, inventory and analysis, and health monitoring, which is an integral part of NASA’s Earth to Science Action strategy. In addition, new capabilities will unlock applications that support water quality and aquatic health assessments (e.g., cyanobacteria blooms), crop production and soil conservation (e.g., crop residues and non-photosynthetic vegetation), climate and snow dynamics research (e.g., snow grain size and albedo), and mineral mapping based on thermal emissivity. This talk will focus on the technical evolution and unique features of Landsat Next’s architecture, and prepare users for forest applications and breakthrough science opportunities using Landsat Analysis Ready Data; cloud computing tools for efficient management and processing; novel artificial intelligence and machine learning algorithms; harmonized data from virtual constellations; scaling from field to airborne and satellite observations; and novel web-based tools and user-friendly interfaces to facilitate the efficiency and effectiveness of researcher-stakeholder engagement.

Forest Resilience to Tropical Cyclones in Subtropical Rainforests assessed by Wind modelling and repeated Airborne LiDAR surveys

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Tropical cyclones cause widespread damage and mortality in natural forest ecosystems. Previous studies in plantations have shown that critical wind speeds depend on forest type and structure. These trends are, however, less clear for natural forests on rugged landscapes since the actual wind load experienced by trees are challenging to estimate and large datasets on forest height changes are difficult to collect.

Here we present findings on forest wind susceptibility by studying wet subtropical forests in Hong Kong affected by Typhoon Mangkhut in 2018. The region is currently in a >70-year restoration trajectory and contains a mosaic of natural rainforests and exotic plantations on a rugged landscape. Changes in forest structure caused by the Typhoon Mangkhut was captured in repeated LiDAR datasets collected in years 2010, 2017, and 2020. We used computational fluid dynamics (CFD) modelling to estimate the wind load experienced by trees and compared it with LiDAR-derived canopy metrics.

Local forest heights were found to be strongly limited by wind, more so than by any other environmental factors considered. These height limits were attributable to the disproportionate damage incurred by the tallest trees during extreme tropical cyclones. Interestingly, forests exposed to relatively high long-term-average wind speeds were relatively unaffected by the typhoon, indicating that exposed forests were structurally acclimated to wind. We also found plantations to be more susceptible to typhoons than natural rainforests of comparable stature. The study represents the first detailed analysis of forest resistance to cyclones within complex tropical landscapes.

Repeat GEDI footprints enable the measurement of moderate-scale tropical forest disturbance

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Introduction/Aim: More of the Amazon rainforest is disturbed each year than completely deforested, but the impact of these disturbances on the carbon cycle remains poorly understood. Recent algorithmic advances using optical and radar remote sensing have improved detection of disturbances at fine spatiotemporal resolution, but quantifying changes in forest structure and biomass associated with these detected disturbances has proven challenging.

Methods: The Global Ecosystem Dynamics Investigation (GEDI), a novel spaceborne LiDAR system, has captured billions of 25-meter diameter footprints measuring forest height, plant area, and understory structure since it began collecting data in 2019. Though it has no guaranteed repeat cycle, GEDI often measured nearby locations several times; some of these near-coincident footprints happen to fall before and after a detected disturbance. In this work, we develop a general-purpose open-source pipeline for identifying these locations and use it to find over 13,700 near-coincident footprint pairs with intermediate disturbance events across the Amazon basin. We also identify a control set of ~65,000 coincident footprint pairs from disturbed areas but without intermediate disturbance events.

Results: Analysis of this continent-scale dataset demonstrates that GEDI can measure statistically significant canopy height and biomass deficits following non-deforestation disturbances as small as 30 m wide. We find varied effects of different disturbance types, including areas where the upper canopy retains most of its original height, but the understory suffers substantial losses. Finally, we model the relationship between a disturbance intensity index based on Landsat alone and GEDI-estimated percent biomass loss.

Conclusion: This work represents an important step towards the development of a pan-tropical, spatially explicit system for tracking carbon losses and structural changes arising from forest disturbance.

Characterising Leaf Phenology of Tropical Forest Trees with repeated Drone Multispectral and LiDAR Surveys

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Leaf phenology plays a crucial role in carbon and water cycling within tropical ecosystems, yet significant uncertainties persist regarding the timing of leaf cycling among tropical tree species and the underlying environmental and physiological mechanisms governing these patterns. The advent of drone-mounted sensors has substantially enhanced our ability to monitor biodiverse tropical forests with high spatiotemporal resolution.

In a study conducted in the tropical moist forests of French Guiana, we monitored the leafing phenology of 3000 tree crowns over two and a half years using lidar and photographic surveys conducted every three weeks. Through these surveys, we were able to track changes in Plant Area Density (PAD) and greenness (Green Leaf Index; GLI) of individual tree crowns over time, particularly focusing on variations in leaf quantity and quality in response to the short dry seasons prevalent in the region.

Our analysis involved calculating the periodicity, synchronicity, and regularity of phenological signals, as well as determining the seasonality and timing of leaf flushing and shedding for 100 dominant species. We observed distinct leaf phenology patterns among species, hypothesizing that these differences are related to species-specific resource acquisition strategies and local environmental heterogeneity.

The majority of tree species exhibited a leaf cycle period close to one year, with some displaying shorter-term cycles or cycles approaching two years. Approximately half of the species demonstrated statistically significant "seasonality" in leaf flushing and shedding. Most species tended to flush new leaves around the transition from wet to dry seasons. Interspecific variation in leaf phenology was strongly correlated with local topographic position (TPI) preference and tree height. Taller species tended to flush fresh leaves earlier relative to the dry season, particularly those associated with gully locations (low TPI). In contrast, species associated with ridges (high TPI) did not exhibit this pattern, suggesting a response to water stress.

The strength and synchronicity of leaf cycling signals were greater for species associated with ridges, indicating a heightened sensitivity to environmental cues among species in better-drained areas. Taller species generally displayed shorter leaf cycle periods, potentially reflecting a faster resource acquisition strategy required for canopy emergence.

Intraspecific variation in leaf phenology timing was linked to tree height, with taller trees tending to flush leaves earlier. Additionally, intraspecific variation in leaf cycle period was greatest at high TPI, suggesting a facultative exchange strategy.

Our findings suggest that leaf phenological traits are adaptable for opportunistic niche filling rather than being closely tied to evolutionary history. Incorporating additional leaf and wood traits into future studies would facilitate a more precise understanding of leaf phenology and its relationship to resource acquisition strategy. Furthermore, linking tree-level variations in leaf characteristics to observed fluxes can provide insights into how individual tree crowns contribute to seasonal patterns of forest productivity.

Comparison and validation of multiple QSM algorithms against destructively sampled biomass measurements

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Introduction/Aim:
Terrestrial laser scanning (TLS, also terrestrial LiDAR) has proven its ability to capture in-situ forest structure with sufficient detail to estimate individual tree biomass and topology. Therefore, TLS currently plays an important role in validation and calibration of both site-specific and global aboveground biomass and forest structure studies. Quantitative structure models (QSMs) that convert point clouds into volumetric 3D models have been instrumental in the process of deriving tree structure and biomass estimates from tree point clouds. Despite the availability of multiple QSM algorithms, there is no standardized benchmarking procedure present and there is an apparent scarcity of open-source validation data. The objectives of this work are to validate existing and previous research utilizing these algorithms, to propose avenues for the future development of QSMs, and to establish a framework for future validation efforts.

Methods:
Here, we utilized a combined dataset from four previous studies of co-incident TLS scans and destructively measured AGB to compare and contrast multiple different QSM reconstruction methods, including *TreeQSM v2.0, TreeQSM v2.4.1,* and *AdTree*. An additional QSM reconstruction method, *RayCloudTools,* will also be added to the comparison in the future. The combined dataset consists of 144 trees from Australia, Belgium, Guyana, and Brazil, and includes both conifer and hardwood point clouds across 14 different species. Point clouds that were obtained in "leaf-on" conditions were leaf-wood separated using the PointTransformer deep learning architecture that was trained on a dataset of manually segmented tree point clouds (Van den Broeck et al., 2024; in preparation). QSM based volumes were obtained using each algorithm and compared to the destructive sampling values. Additional analysis focused on understanding the allocation of volume within generated QSMs, and the effect of point cloud quality on the biomass estimates.

Results:
Results show significant variation in the overall ability for different QSM algorithms to estimate total tree biomass. *TreeQSM v2.4.1* demonstrated a large amount of variability of biomass estimated, as well as a large biomass overestimation (an average of 3.8 times the destructive values; CCC = 0.62), while *AdTree* performed better (CCC = 0.82), and *TreeQSM v2.0* was the most accurate (CCC = 0.98). The analysis for *RayCloudTools* estimates are currently being processed. Additionally, there is a variable effect of point cloud quality in the generated tree volumes from different models. Furthermore, the stability, ease of use, and accessibility varied greatly between tested algorithms, which is important to weigh against quantitative results.

Conclusion:
Validation and benchmarking of QSM algorithms against each other will lead to increased data-interoperability of LiDAR-based biomass and structure estimates. Additionally, the importance of cultivating pipelines to easily acquire high-quality LiDAR data is once again underlined, as there is a clear improvement in QSM model quality alongside point cloud quality. We hope to make full use of the open-source validation data that is available, and to further explore potential validation and benchmarking procedures.

Comparing the Accuracy of Wall-to-Wall ITD Inventory Products to Regional AGB Estimations for Forest Planning and Operations

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The Confederated Tribes of the Colville Reservation, the Confederated Salish Kootenai Tribes, and the Yakama Nation have collected high resolution aerial LiDAR across their operational forested landscapes within Washington and Montana during 2022, 2021, and 2019, respectively. These LiDAR datasets have been processed through the ForestView® software to result in Digital Inventory® geographic information system (GIS) compatible operational tools for quantification, planning, valuation, and fire risk classifications of their resources. Additionally, the United States National Aeronautics and Space Administration (NASA) Carbon Monitoring System has developed above ground biomass (AGB) classifications across the western U.S. for planning and carbon sequestration assessments. This research summarizes and compares the results of these alternative landscape assessment products, to geolocated field data collected simultaneously with each LiDAR acquisition, on these diverse and managed landscapes. Comparison of accuracies at the watershed, operational “stand”, and plot resolutions are presented to inform management objectives. Discussion of accuracy at these three scales is presented to inform decisionmaker considerations with regard to both landscape planning efforts and site-specific operational decisions.

How early can we detect European spruce bark beetle attack using hyperspectral drone images with high spatial- and temporal resolution?

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The European spruce bark beetle (*Ips typographus*) is one of the main threats to coniferous forests in Central and Northern Europe, causing severe damage to Norway spruce (*Picea abies*). In Sweden, extreme events of drought and windstorms have become more frequent, resulting in peaks of bark beetle population and large outbreaks over the last few years.

Detecting infestations as early as possible is essential to effectively apply control measures (e.g., removal of deadwood, sanitary cuttings) and prevent further dissemination. However, detecting trees during the green attack stage is a challenge, since the crowns do not present symptoms visible to the human eye during this phase. Nevertheless, remote sensing technologies can be great allies to capture changes in tree physiological conditions. In particular, hyperspectral images (HSI) can reveal detailed information on the spectral signatures of the vegetation, which could enable the detection of anomalies exhibited by attacked trees.

In this study, we aim to investigate the potential of HSI for the early detection of European spruce bark beetle attack in Southern Sweden. A time-series of high-resolution HSI was acquired between the weeks 16 and 32 of 2023 in a controlled experiment in Remningstorp, in south-western Sweden (58°27'3.51"N, 13°39'51.64"E). We studied 24 circular plots distributed across four stands of Norway spruce forest. Each plot had a 15 meter radius and 42 trees on average. We used the hyperspectral cameras AFX10 and AFX17 mounted on a drone to capture spectral data ranging from 400 to 1700 nm. The acquired images have 112 spectral bands, providing a pixel size of 7 and 11 cm with the used configuration, respectively. Reference panels with known reflectance were used to correct for atmospheric and illumination effects. Simultaneously, a weekly field inventory was conducted to record indication on bark beetle damage in the plots (i.e., holes, dust, resin, bark damage, crown discoloration, and crown defoliation).

We use a tree crown segmentation to extract the spectral information at the individual-tree level. By matching this information with the field inventory data, we will be able to compare the spectral signatures of attacked and non-attacked trees. We will identify which are the spectral bands that provide the highest separability between these groups. Furthermore, we will test the performance of vegetation indexes commonly used to characterize vegetation health (e.g., NDVI, GNDVI, NDRE, NDWI, DSWI, CVI, CIG, GLI), as well as indices recently proposed in the literature (e.g., Multiple Ratio Disease-Water Stress Indices – MR-DSWI1, MR-DSWI2, MR-DSWI3, and MR-DSWI4; Normalized Distance Red & SWIR – NDRS; Green Shoulder Curvature Ratios – GSCR1 and GSCR2) to identify attacked trees. Finally, we will analyse the continuous spectrum of wavelengths to possibly identify better relationships that enable earlier identification of bark beetle attack.

We expect this study to improve our understanding of the potential of HSI to detect bark beetle attack in early stages. With development, our findings could contribute to monitoring systems of forest disturbances and increase the success of management efforts towards heathy forests.

Multiband Sandwiches - Using Multispectral Imagery with Neural Networks to find Kahikatea trees across New Zealand

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Forests that have been dramatically depleted relative to their prehuman extent are being replanted around the country; due to the varied geographic distribution of planting efforts, tracking progress remotely is essential. The availability of satellite information combined with accessible machine learning algorithms allows for environmental sensing to happen at a near autonomous level. The Eco-index Team have been using this approach to assist with the restoration efforts of native ecosystems in Aotearoa. With an initial goal to find kahikatea (*Dacrycarpus dacrydioides*) stands, we have developed a detection framework; it uses a combination of high resolution PlanetScope multispectral imagery, multiple open source satellite datasets and regional council and restoration group validation data sources. While powerful for prediction, this approach results in various challenges, including: varying image resolution and dimensions across multiple sources, management of large datasets, and scaling the predictions. NumPy arrays provide an effective way of combining various dimensional datasets into a data cube (or ‘multiband sandwich’) structure. Additionally, the framework outlines clear pathways for handling large datasets on local hardware and provides a simplified method for scalability to the national level. Within this framework, our detector is are currently capturing kahikatea trees across the Waikato region with a computation time of approximately 1 week. This relatively quick detection turnaround time provides a platform to monitor ecosystems through seasonal and annual changes. Future applications of the detector will include deployment on a national scale, predicting age of restoration areas using available historic satellite imagery, and monitoring the health of the growing ecosystems. Broadly, provided that there is sufficient training data to feed into the modelling process, our framework provides a means of detecting any type of land cover.

Guiding Assisted Migration Amidst Climate Change: Refining Site Selection for Sugar Maple with Fine-Scale Spatial Distribution Modeling

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Climate change poses uncertainties and challenges for forestry practices, necessitating adaptive measures to protect forests and their services. Assisted migration (AM) supports adaptation strategies to conserve ecosystems and maintain forest production. To facilitate its implementation, spatial distribution models utilizing multivariate approaches, incorporating climate, soil, and topographical factors, can help assess habitat suitability for tree species. In these models, high accuracy terrain data derived from LiDAR enables the characterization of variables such as elevation, slope, aspect, solar insolation, terrain curvature, topographic position and others, and in turn, allows climate data downscaling, which are key components of the fine-scale representation of ecological processes required to support silvicultural action. Previous research efforts suggest that the habitats of several tree species in North America are likely to expand northward due to climate change. However, this expansion may not occur linearly and uniformly in time and space. In this study, we use high accuracy terrain data to gain insights into the ecological requirements of sugar maple (SM) (Acer saccharum) and propose effective silvicultural strategies for its survival and growth in a changing climate. Sugar maple is a commercially valuable species in North America whose range is expected to shift northwards in response to climate change. We used a Random Forest classification model to investigate how climate, soil, and topographic features can help identify suitable SM habitats at a fine scale in the current climate. The study area (863 km^2) was selected to encompass a gradient of conditions at the northern edge of the species' range. It is located within mixed wood forests in Quebec, Canada, at the transition between temperate and boreal zones. Results revealed that soil variables and topographical characteristics were the most important determinants of SM presence at the landscape level, followed by local climate variables. Slope and tangential curvature showed that SM was more likely to be present at the top of the hills at the northern edge of its distribution range, where it can avoid damage from cold air drainage and/or accumulation. The model was then run using future climate projections to determine which sites may become more suitable to the species over time. Results suggest the species' habitat may expand downslope towards valleys with minor increases in precipitation, degree days above 0 ºC and temperature averages. Despite a significant proportion of the area likely to remain stable, the study region shows an important increase in suitable sites, but also areas where SM currently occurs that will become less suitable to the species within 30 years under one of the most optimistic climate scenarios (SSP1 2.6, 2011-2040). Our results can support the implementation of AM at the stand level scale with spatially explicit representations that provide practical references for practitioners to guide silvicultural action. The results also highlight that certain changes in specific areas are likely to occur more rapidly than expected, necessitating swift silvicultural responses.

Improving woodland clearing and regrowth detection using imaging radar

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Introduction/Aim: Global, long-term data sets from optical satellite sensors, e.g. Landsat and Sentinel-2 series, are primarily used to detect and produce annual clearing and regrowth maps for Queensland, Australia. These products are used for statewide programs including conservation and bushfire mapping, Reef Water Quality Protection, and compliance assessment, as well as contributing to international reporting requirements on carbon and the recent European Union Deforestation Regulation.

Queensland is known for its high rates of deforestation and imaging radar offers potential for improving detection and accuracy of both clearing events and regrowth. Imaging Radar is already being used in several disturbance warning systems in tropical forests, but has been used to a lesser extent in spatially heterogenous woodlands.

Methods: A combination of optical (Sentinel-2) and radar imagery (Sentinel-1) was used to explore the distribution and extent of clearing and regrowth in different vegetation communities. The work was conducted in a woodland, sub-tropical savanna environment as part of the Injune Landscape Collaborative Project test site. After identifying backscatter signatures associated with clearing and regrowth, deep learning models were explored to determine which offers the most improvement over the current Landsat/Sentinel-2 methodology. Mapping results from L-band ALOS PALSAR data were also compared with the C-band Sentinel-1 results to assess how effective each radar band (L versus C) was.

Results: Backscatter signatures associated with clearing and regrowth were identified in the different vegetation communities. Work is now underway to develop a deep learning approach using the optical and radar imagery to detect clearing over larger areas on a repeated basis. This will be done through publicly available python scripts to automate ingestion and pre-processing of radar imagery to map clearing and regrowth products.

Conclusion: This work presented a preliminary demonstration of the abilities of globally available, and regularly updated, radar data sets to detect vegetation clearing and regrowth in a sub-tropical woodland savanna environment. Further work is required to determine how to scale this to work in other non-savanna vegetation communities, on a regular basis.

The impact of late spring frost and summer heat waves on forests of the Italian Alps analyzed through Sentinel-2 multi-temporal images

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Introduction/Aim
Extreme climate events (ECEs), such as severe droughts, heat waves, or late spring frosts, exert significant influence on forest ecosystems and their frequency is forecasted to increase thanks to climate warming, posing a threat to the sustainability of forests. Among ECEs in this study we focused on late spring frost (LSF) and summer heat waves (SHW). Projections indicate that both SHW and LSF will increase in the future in temperate and boreal forests. Time series of remote sensing data, in particular satellite multispectral images with frequent revisit time and high spatial resolution such as Sentinel-2 could be very useful to analyse both the effect of such events on forests and the recovery of forests after the events.

Methods
The studied area was the forested areas of the Autonomous Province of Trento (about 3000 kmq), in the Italian Alps, where a LSF event occurred in May 2019 and a SHW occurred in July 2022. 281,525 sampling points distributed on a grid of 40 by 40 m were distributed over the studies area covering 16 tree species and ranging from 100 to 2000 meters a.s.l.. Sentinel-2 satellite images spanning from April 2018 to October 2023 were used to extract NDVI (Normalised Difference Vegetation Index) values for each point. NDVI was interpolated using a GAM function to obtain a daily for each point for the interval 2018-2023. Daily average temperatures from 100 weather stations distributed over the studied area were spatialized using a kriging spatial interpolation. Phenological metrics like Greenup, Maturity and Senescence were extracted for each point using phenofit R package. Wilcoxon-Mann-Whitney test was used to determine the time periods where i) the daily temperatures of 2019 and 2022 were significantly lower or higher than the average 2018-23, and ii) the NDVI values in 2019 and 2022 were significantly different from the average 2018-23 Data were analysed by species and by elevation intervals.

Results
The 2019 LSF affected mainly species located between 1000 and 1300 m a.s.l., in particular European beech. The effect was different according to the elevation: i) for sampling points located below 750 m a.s.l. NDVI values were in line with the average 2018-2023; ii) for points between 1000 and 1250 m a.s.l. NDVI increased slowly compared to the average 2018-23 and reached its peak later maintaining values below the average for the entire 2019; and iii) for points above 1250 m a.s.l. there was a shift in the start of the growing season, but then the NDVI values were similar to the ones of the season 2018-2022.
The 2022 SHW affected negatively mainly species located at low elevations, while species located at high elevations experienced an increase in NDVI values compared to the period 2018-2023. Evergreen oak, was the species that suffered the most, and it recovered only the year after (2023). European beech and Norway spruce that in the study area are mainly located above 1000 m a.s.l. in 2022 showed NDVI values higher than the average, with a slight decrease in July for European beech.

Potential of Remote Sensing for quantifying multi-taxon biodiversity in Mediterranean mountain forests

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Introduction: Biodiversity monitoring represents a major challenge to support proper forest ecosystem management and biodiversity conservation. The latter is indeed shifting in recent years from single-species to multi-taxon approaches. In this context, remote sensing is a powerful tool, continuously providing consistent and open access data at different spatial and temporal scales. Particularly, Landsat Time Series (TS), Sentinel-2 (S2) and Airborne Laser Scanning data (ALS) have great potential to produce reliable proxies for biological diversity.

Methods: In 140 plots of beech and silver fir forests in central Italy, we sampled the beetle fauna, breeding birds, epiphytic lichens, and Tree related Microhabitats (TreMs).
First study area consists of four monitoring sectors in a Mediterranean-managed beech forest located in the Apennines (Molise, Italy). The second area located in beech forests of two Italian National Parks (Gran Sasso and Cilento National Parks), and the third study area located in the Nature Reserve of Vallombrosa (Tuscany, Italy).

Results: In all areas we calculated Shannon's entropy and Simpson's diversity. In the first area, the capability of Landsat Temporal Metrics in predicting the richness of saproxylic beetles family and trophic categories was assessed in terms of Pearson's product-moment correlation. The alpha diversity and species richness analysis indicate dissimilarities across the four monitored sectors (Shannon and Simpson's index ranging between 0.67 to 2.31 and 0.69 to 0.88, respectively), with Landsat TS resulting in effective predictors for estimating saproxylic beetle richness.
In the second area, we assessed the correlation with S2 harmonic metrics, biodiversity indices, and forest structural variables. The diversity indices were higher for the multi-taxon community compared to single taxa. The highest correlation values between S2 data and biodiversity indices were recorded in Cilento for multi-taxon and beetle communities ($|r|$ = 0.52 and 0.38, respectively), and in Gran Sasso for lichen and beetle communities ($|r|$ = 0.34 and 0.26, respectively). RMSE% ranged between 2.53 and 9.99, and between 8.1 and 16.8 for the Simpson and Shannon index, respectively.
In the third area, 240 ALS-derived metrics were calculated: 214 derived from the point cloud, 14 derived from a rasterized canopy height model, and 12 consisting of RGB spectral statistics. The final models were used to produce wall-to-wall maps of each biodiversity index. The RMSE% of the final models ranged between 8.5% (birds' Shannon index) and 50.2% (epixylic TreM types' Shannon index). The dependent variable that obtained the best performance was the Shannon index for each group considered, except for the epixylic TreMs, with a mean difference of -6.7%. Likewise, the highest R2 was for the Shannon index (0.17, against 0.14 for the richness).

Conclusion: Our results confirm and strengthen the importance of Remote Sensing data to assess forest biodiversity indicators that are relevant for monitoring forest habitat and predicting environmental complexity despite the many factors influencing multi-taxon biodiversity. The proposed methods support quantifying and monitoring the measures needed to implement better forest stand and multi-taxon biodiversity conservation.

European mapping of Forest Disturbances and Vulnerability: First results of the FORWARDS project

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Climate change and environmental stressors negatively affect forest ecosystems and biodiversity. The limited availability of data hinders understanding of how forests adapt to climate change and the impacts of forest management. Thus, standardized monitoring initiatives across Europe is crucial for effective planning and mitigation. The EU Forestry Strategy prioritizes indeed sustainable management for biodiversity and climate resilience and recognizes climate-smart forestry and restoration as global solutions.
In this context, the FORWARDS project aims to bridge the current separation in the EU between ground and satellite forest information and to develop the ForestWard Observatory - a European observatory for forest climate change impacts. Within this framework and relying on the Google Earth Engine cloud computing capabilities, we processed approximately two hundred thousand Landsat images to provide four decades (1984-2023) of Europe-wide disturbance mapping and characterization. More in detail, for each detected forest change we predicted several parameters including the severity of the disturbance, the persistence, and the number of years the forest needed to recover. Based on this detailed disturbance characterization, we estimated, for each disturbed pixel, the vulnerability of the forest to that forest disturbance. As a result of these calculations, we obtained a forest disturbance data cube that contains comprehensive and exhaustive information on European forest disturbances. On the other hand, analyzing and understanding a so large dataset may be challenging. Indeed, aiming to implement a European forest observatory, it can be challenging to extract meaningful information depending on the many analyses of interest.
To overcome this issue, we developed a Google Earth Engine application that allows visualizing, filtering, and downloading each parameter of detected forest disturbances. Indeed, while we are constructing a forest disturbance map for each analyzed year, and while for each pixel we predict multiple disturbances that occurred over time, using our application users can visualize for each pixel the most severe or the most recent disturbance, but also, for example, the disturbance that led to the fastest photosynthetic activity recover. Similarly, users can filter out changes depending on the year, the disturbance severity, the persistence, or the recovery rate. All of this information will play a key role in understanding European disturbances and will constitute the basis for wall-to-wall mapping of European forests' vulnerability and resilience.

GEDI and Sentinel Integration for Quantification of Poplar Plantation Stocks

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Introduction
Agroforestry represents a strategic asset to contrast climate changes and environmental impacts of agriculture intensifications and a natural-based solution for landscape resilience. Particularly, poplar plantations, thanks to their fast growth rate, conserve and create ecological networks in homogeneous agricultural land, together with the production of plywood, high demanded by several industries, ensuring the storage of a large amount of CO_2 in durable manufactured products. Owing to rapid growth, short rotation features, and the dependency on the timber price market, poplar plantations are characterized by large inter-annual fluctuations in their extent and distribution. Therefore, monitoring poplar plantations requires a frequent update of information that is not feasible for conventional National Forest Inventories due to their periodicity. Remote sensing emerges as the most suitable tool for monitoring, both for mapping poplar plantation locations and for more in-depth estimation of structural plantation variables. Accordingly, our goal was to estimate the amount of aboveground biomass and carbon stocks in a large flat study area (more than 46 000 km^2) in Po Valley (Northern Italy).

Methods
To do so, we developed a deep learning model based on multi-stream remote sensing measurements to create a high-resolution canopy height map. Our deep learning U-Net model uses multi-band images from Sentinel-1 and Sentinel-2 with composite time averages as input to predict tree height derived from GEDI waveforms. The model outputs allow us to generate a 10 m resolution canopy height map (CHM) of the whole Po Valley for 2021, with a mean absolute error of 2.6 m on external validation data from forest inventory plots. Moreover, based on previous studies, yearly poplar plantations maps in the study area were available. Therefore, based on the poplar-specific yield table carried out through terrestrial laser scanner data in plantations included in our study area and the modelled CHM, we estimated the growing stock volume (GSV), aboveground biomass (AGB), and carbon stock (CS) in all poplar plantation stands.

Results
The results were compared with available data from field surveys. The RMSE was 19%, 30%, and 37% for DBH, H and GSV, respectively. The estimated average GSV was 70 m^3 ha^{-1}, while the AGB and total CS were 23 Mg d.m. ha^{-1} and 12 MgC ha^{-1}, respectively. The poplar plantation map update for 2022 allowed us to estimate the total harvested GSV of poplar trees cut and destined for industrial purposes to be 370 000 $m^{3,}$ corresponding to 66 000 MgC ha^{-1}. The average harvested area was 1.5 ha from which an average of 130 m^3 was obtained.

Conclusion
The integration of multiple remotely sensed data and new machine learning approaches enables the monitoring of dynamic forests such as poplar plantations, not only spatially but also in quantifying variables critical to climate change mitigation, such as carbon stock estimation for durable goods.

Tree species classification using automatically annotated multispectral aerial laser scanner data.

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Understanding tree species composition is critical in forest assessments. While Convolutional Neural Networks (CNNs) and Aerial Laser Scanner (ALS) can be effective modelling tools, annotating tree-level data proves itself challenging and time-consuming. On the other hand, spatially explicit data on forests, as harvester production reports (HPR), can become more common in the future and be used for annotation. Thus, we propose a method of tree species classification that uses automatically annotated multispectral ALS point clouds.

The ALS data was collected in 17 stands in southern Sweden (59°46´N, 14°31´E). The stands were scanned in September 2021 using the Finnish Geospatial Institute's multispectral ALS system (Hakula et al., 2023) composed by two sensors, the Riegl miniVUX-1UAV 905 nm (Channel 1), and the Riegl VUX-1HA 1550 nm (Channel 2). The resulting point cloud had approximately 1000 points/m^2. The ALS point clouds were segmented into individual trees according to Holmgren et al. (2022).

Between November 2021 and October 2022, 69,253 trees were harvested from the 17 stands using harvesters equipped with a positioning system. The HPR files stored 4 species classes, "Norway spruce", "Scots pine", "Birch", and "Other broadleaves". The "Birch" and "Other broadleaves" classes were combined into a single "Deciduous" class. The trees segmented from the ALS data were automatically linked to the tree positions present in the harvester files based on the distance between the trees in both datasets, creating an annotated ALS dataset. Altogether, 45,516 harvested trees were linked to an ALS derived tree segment.

After linking both datasets, a CNN originally designed for 2D image classification was employed for predicting tree species. To adapt 3D point clouds for this 2D-CNN, we converted them into images from four perspectives. This transformation was done by rasterizing point clouds along the X (Lat.) vs. Z (Height) axis, generating four 2D representations per tree, each rotated around the Z axis at 45° intervals. The CNN was trained to classify 3 tree species classes according to the harvester data used for annotation, namely Pine, Spruce and Deciduous. The images were created using an RGB false color composite combining channels 1 and 2. In each pixel, the red color was assigned the mean intensity of channel 1 (905 nm), green as the mean intensity of channel 2 (1550 nm), and blue as the Normalized Near Infrared Index (NDII), calculated using channels 1 and 2. Finally, the resulting RGB images were resized to the standard dimension of 160 (width) by 320 (height) pixels.

The tree species classification had an overall accuracy of 93.2%. The tree species classes showed F1 scores ranging from 0.923 to 0.942 from Spruce to Deciduous, resulting in a macro F1 of 0.934. In summary, spatially explicit harvester production reports can be efficiently used to annotate remote sensing based models at individual tree-level.

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235

The potential of West and Central African coastal protected areas for Blue Carbon projects and mangrove restoration

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Despite the well documented ecological, economic and social benefits they provide, mangroves continue to suffer high rates of degradation and destruction, with global losses of 1-2% per year, exceeding those of terrestrial tropical forests. The West-African mangroves, approximately 11% of the world’s mangrove area, constitute a major carbon sink at the global scale, and their protection is a priority in the context of climate change. Coastal conservation projects in West-African Marine Protected Areas (MPAs) have suffered from a lack of local funding and relies heavily on international funding sources, a less than ideal solution in the long run. Thus, finding local, durable funding solutions is a priority for these protected areas. The goal is to assist in the development of pathways for blue carbon projects in West Africa to access blue carbon finance and promote regional cooperation for climate change mitigation and adaptation through the restoration, conservation and sustainable use of mangroves at local, national and regional scale.
To achieve this, we propose the development of mapping and monitoring approaches using remote sensing in order to evaluate the potential to put together Blue Carbon projects on the MPAs. We used a Landsat-based compositing approach (LandTrendr) and machine learning classifiers to develop annual land cover (eight key land cover classes, including mangrove forests, from 2000 to 2022) for approximately 275,000 Km² along the coast from Mauritania to the Democratic Republic of Congo, covering more than 235 MPAs. The yearly trend of land cover and mangrove extent allowed to identify restorable areas and key coastal MPAs to develop projects to be financed by the carbon credit market for climate change mitigation and adaptation.

Identifying deforestation drivers in Cameroon using deep learning and Earth observation data

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Sub-Saharan Africa has become the region with the largest annual forest loss between 2010 and 2020, with 3.9 million hectares lost per year. It has also experienced the fastest agricultural expansion globally since 2015. Within the Congo Basin, where the second largest tropical forest in the world can be found, Cameroon has known the sharpest average annual rise in primary forest and tree cover loss between 2016 and 2021. Further understanding of the drivers of forest loss with a high level of detail and automation for up-to-date information is needed to: plan interventions focusing on specific areas and actions, design measures to address specific drivers, and define priorities for monitoring. However, a detailed, country-specific and comprehensive automated classification for the land-use changes leading to deforestation is lacking for Cameroon.

Here, we present Cam-ForestNet, a new deep-learning approach to automatically classify fifteen direct drivers of degradation and deforestation for Cameroon, combined with a newly-consolidated satellite imagery reference dataset. For this purpose, we compared the performance of different optical and SAR data (including Landsat-8, NICIFI PlanetScope, Sentinel-1, and Sentinel-2), different band combinations, and tested multi-sensor data fusion and time-series analyses. In addition, we assessed the contribution of auxiliary socio-economic and biophysical parameters for the identification of direct and indirect deforestation drivers, and their potential for predicting future threats and land use changes. Our results show the potential of Cam-ForestNet to monitor deforestation and prioritise interventions for organisations working on forest conservation, as well as to carry out post-event analyses to inform policy. This model is especially powerful as it displays a high performance in identifying detailed small-scale drivers, which is typically challenging.

We also explore the considerations and precautions needed to allow for the use of the method in ‘real-world’ applications including, for example: 1) the need for an interpretable confidence score, 2) an easy-to-use and easy-to-update platform, 3) in-country collaborations and engagement with various stakeholders, and 4) careful open data strategies with attention to privacy and security issues. Finally, we discuss the potential of using our framework for other locations in the Congo Basin area.

Estimating Forest metrics in Interior Alaska: Mobile, Terrestrial, and Aerial LiDAR.

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Boreal Forests make up 30% of global forested area and are warming four times faster than the global average. To understand how these dense boreal forests are responding to climate change, accurate models of forest structure are needed. Fine scale remote sensing platforms such as terrestrial and mobile Lidar sensors, can fulfill this need by providing high resolution models of individual trees. However, the modality of Lidar acquisition, measurement scale, and forest type on model performance is not well understood in boreal forests. In this study, we investigate the capabilities of ground-level local extent Lidar instruments and its utility in upscaling to the regional extent of aerial Lidar. Our study area was in Campbell Tract Special Recreation Management Area near Anchorage Alaska. Field work collecting MLS and TLS scans was conducted in September 2022. ALS scans were collected the same year using NASA Goddard's Lidar Hyperspectral and Thermal (G-LiHT) airborne remote sensing system. This location was chosen for its accessibility, for having forests with characteristics typical of interior Alaska, and for having pre-established Forest Inventory Analysis (FIA) sites. The FIA program is a nationwide inventory of all forested lands lead by the US Forest Service, they collect individual tree data such as species, height, and diameter. All Lidar scans were collected on FIA plots. First, we compare the usability of different ground level instruments in the field and the accuracy and of calculating forest structural metric such as diameter, height, and volume in boreal forests. We collected scans with a multi-scan stationary terrestrial laser scanner (TLS) and hand-held mobile laser scanners (MLS). Second, we upscale our structural metrics to the regional extent by calibrating the metrics calculated from an aerial laser scanner (ALS) to those from the ground-level instruments. Preliminary analysis indicate MLS devices are more practical and efficient for data collection, they are approximately 5x faster at collecting complete plot scan than the TLS devices. Single scan MLS devices also require less pre-processing time than multi-scan TLS. We applied a segmentation algorithm for stem detection in dense vegetation on the MLS and TLS scans providing metrics for height, stem count, volume, and DBH. For ALS we used a top-down approach to segment trees and calculate height and stem count. We created a model using the observed relationship between height and DBH calculated from the MLS and TLS, and used it to estimate DBH for the ALS scans. Then using the estimated DBH and height we estimated volume for the ALS scans and compared it the TLS and MLS findings. We validated our findings with Forest Inventory Analysis census data collected the same year by comparing calculated DBH, height, and stem count with manually measured values. Preliminary results indicate MLS and TLS devices provide more accurate structural metrics at the tree and plot level. However, ALS estimations can be improved with calibration to ground level scans. These comparisons will inform the development of a long-term monitoring strategy and direct future management strategies for boreal forests.

Enhancing the Validation of Drone LIDAR Forest Biomass Retrieval Algorithms through a Comprehensive Simulation Framework

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The quantification of above ground biomass is pivotal in forest ecology and management, underpinning the assessment of forest health, productivity, and sustainability. Despite advancements in Terrestrial LiDAR technology enabling the automated extraction of detailed structural attributes, its application remains largely confined to smaller regions (<1 ha). This limitation underscores the necessity for more scalable methods that can extend the benefits of LiDAR technology. Our research aims to address this by focusing on the validation of drone-based LiDAR (UAV-LS) algorithms for woody volume estimation (underpinning woody biomass estimation), specifically through the evaluation of RayExtract, a component of the open-source RayCloudtools library.

RayExtract is at the forefront of deriving woody volume metrics from plot-level LiDAR point clouds, offering a pathway to rapid and extensive biomass assessments. However, the validation of such algorithms has been hindered by a notable scarcity of reference data at the required scale. To tackle this challenge, we have developed a novel validation framework that incorporates UAV-LS simulations of three synthetic forests across a gradient of structural complexity. These synthetic forests are representations or digital twins of diverse long-term monitoring Terrestrial Ecosystem Research Network (TERN) sites in Australia. This approach allows for an exhaustive and precise evaluation of algorithm performance at multi-hectare scales, assessing the impact of data quality, sensor specifications, and survey methodologies on the accuracy of woody volume estimations across a spectrum of simulated forest environments. Preliminary results indicate an inverse relationship between point density and woody volume estimation when compared to the synthetic reference.

Utilizing this validation framework, our study demonstrates the efficacy of RayExtract in deriving accurate woody volume information from a range of input qualities, showcasing its potential for application in broad-scale (100’s ha) forest management initiatives. Our research contributes to improving the accuracy of forest biomass measurements, thereby facilitating better-informed decisions in carbon accounting, timber production, forest health monitoring, and ecological research. Furthermore, this framework offers a promising foundation for the ongoing evaluation and refinement of algorithms dedicated to any structural measurement from LiDAR data. UAV-LS will be a critical component facilitating large-scale calibration and validation of remote sensing satellite methods of 3D forest structure and aboveground biomass.

Evaluating airborne, mobile and terrestrial laser scanning for urban tree inventories: a case study in Ghent, Belgium

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Urban tree inventories rely on accurate structural measurements including tree diameter, tree height, crown projection area and volume for various purposes. These measurements are critical to accurately estimate ecosystem services, evaluate tree growth and make sustainable management decisions. Traditionally, tree measurements are obtained using instruments such as range finders and diameter tape. The accuracy of these traditional methods is highly influenced by the observer's experience, the equipment and the line of sight to tree canopies, and are labour intensive. Nowadays, integrating these measurements into urban tree inventories can be achieved through the use of 3D laser scanning (also known as LiDAR). Different laser scanning platforms exist, both with their own advantages and disadvantages, including different levels of point cloud precision and noise. For both park and street trees in Ghent (Belgium), we investigated how such platforms perform under different leaf conditions. Therefore, we collected laser scanning data of 95 individual trees. We collected terrestrial laser scanning (TLS), mobile laser scanning (MLS) and airborne laser scanning (ALS) in leaf-on (TLS, MLS, ALS) and leaf-off conditions (TLS, MLS). We not only investigate and present the accuracy of these platforms, but also look at practical considerations of scanning in cities. Our findings demonstrate accurate derivation of DBH using TLS and MLS. Crown dimensions on the other hand, more specifically crown volume (BIAS= $-115m^2$, CCC=0.85) and tree height (H MLS leaf-on: -0.39m, CCC=0.99), were underestimated using MLS compared to TLS in leaf-on conditions. However, platform performance was highly dependent on tree dimensions and the complexity of the surroundings. Our results will help city councils and tree managers choose the most optimal LiDAR platform for urban tree inventories, accounting for their purpose, site complexity and budget.

Canopy laser scanning to study the complex architecture of large old trees

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Large trees are keystone structures providing multiple ecosystem functions in forests all around the world: they disproportionately contribute to forest biomass and biodiversity. Large trees can have an extremely complex structure, housing many epiphytes on their stem and branches. High point-density 3D point clouds, in which leaves and epiphytes in the tree can be distinguished, are useful to make the link between the distribution of organisms on the tree, the tree architecture and its microclimate. In addition, a comprehensive branching model can improve above ground biomass (AGB) estimates. Highly detailed, complete point clouds of large trees are, however, exceptionally difficult to derive. With terrestrial laser scanning, the state-of-the-art method to capture 3D tree structure, the plant material blocks the view of (or, occludes) the top part of the dense crown. Drone or airborne laser scanning data on the other hand, lacks detail in the subcanopy. Combining these two methods minimises occlusion; however, increased distance from the tree to the scanner still leads to a relatively low resolution of the canopy point clouds. To improve the level of precision of the tree point clouds, we introduce a new concept, called canopy laser scanning (CLS). With CLS, a laser scanner is operated statically inside the tree canopy, reducing the distance between the area of interest and the instrument. We lifted a high-end laser scanner (RIEGL vz-400(i)) inside the canopy of six large emergent trees. Four of these trees are located in different types of tropical rainforests in Colombia, Brazil and Peru. They are part of biodiversity programs in which organisms and their spatial distributions are studied (Life On Trees, Araçá). The two other trees are famous giants located in the wet temperate eucalypt forests of southern Tasmania. We will present the practical aspects of CLS, evaluate the extra value of using canopy scans, looking at occlusion and point cloud precision, estimate epiphyte cover and AGB. We demonstrate that canopy laser scanning opens up new opportunities in sciences in which multi-disciplinary teams perform in depth research on large individual trees.

Design-based assessment of the accuracy of land use/land cover maps based on remote sensing information

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Introduction: Land use/land cover (LULC) maps are usually obtained through the classification of satellite images. To assess the accuracy of these satellite maps, the magnitude of misclassification errors is measured comparing the map labels to the reference class labels, i.e. the best assessment of ground truth recorded for a probabilistic sample of reference locations. However, misclassifications are likely to be spatially clustered and their presence may vary in different parts of the survey area, determining the necessity of accompanying the satellite map with an accuracy map that shows the spatial distribution of the quality of satellite-based predictions.

Aim: To this end, the estimation of error maps is performed for the first time in a design-based inference perspective, considering that both the true (unknown) map and the satellite map are fixed. Indeed, the true map is fixed because, in a design-based approach, uncertainty only stems from the sampling scheme, while the satellite map is fixed as it is derived from samples of non-probabilistic nature. Consequently, also the matching between true and satellite maps gives rise to a fixed error/non-error surface.

Methods: In this way, the error map can be estimated using the nearest neighbour interpolator (NN) to assign to any unsampled location in the survey area the error/non-error value observed at the nearest reference location.

Results: Under sampling schemes of wide use in environmental surveys, the resulting error maps are asymptotically design-unbiased and consistent, i.e., as the effort in collecting reference samples increases, the interpolated maps approach the true error map. The error map design-consistency has also been checked through a simulation study. The U.S. land cover map and the Italian forest/non forest map are considered as case studies.

Conclusion: Our proposal allows LULC map users to operate fully in a design-based mode when assessing the quality of satellite maps.

Digital forest inventory based on UAV imagery:

Derivation of diameter at breast height through cast shadows of tree stems

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The conventional method of manual data collection for forest inventories, often through labor- and time-intensive field campaigns, is prone to providing uncertain and potentially non-representative samples. While techniques like terrestrial laser scanning provide high-resolution data on individual tree structure, cost and accessibility hinder widespread use. Similarly, intermittent data collection challenges airborne laser scanning, potentially leading to outdated information. Additionally, factors within the German forestry sector, such as climate change-related events, staffing shortages, shifts towards more diverse forests, and the growing emphasis on digitalization strategies, underscore the need for current and accurate digital forest databases.

This study investigates the application of Unoccupied Aerial Vehicles (UAVs) and Structure from Motion (SfM) techniques for conducting digital forest inventories, with the aim of addressing current challenges in sustainable forest monitoring. The research was conducted in the Hainich National Park, Germany, a region characterized by its unmanaged and structurally diverse deciduous forest, primarily composed of beech trees (Fagus sylvatica). A detailed digital representation, including 3D point clouds of the canopy, stems, and ground was generated by combining leaf-on and leaf-off data. Various flight configurations and camera setups were tested to ensure comprehensive data coverage, enabling the derivation of key forest parameters such as stem positions, individual tree crown delineation (ITCD), diameter at breast height (DBH), and coarse wood debris (CWD) using clustering algorithms, deep learning models, and object-based methods. This presentation specifically focuses on the derivation of DBH using a deep learning approach to classify the cast shadows of tree stems.

For the derivation of DBH values on an individual tree basis, UAV RGB data collection is conducted during leaf-off state and under sunny weather conditions. A SfM workflow is applied to process the images, generating a terrain normalized point cloud. Points associated with the canopy and stems are filtered out based on their height information, resulting in an orthomosaic that exclusively represents ground information, including tree cast shadows. A modified U-Net is trained using manually labeled training data and data augmentation. This trained model, in conjunction with rule-based assumptions about the form of shadows, is then used to classify shadow areas. An algorithm is developed to automatically derive DBH by analyzing the classified shadow areas, utilizing stem coordinates derived via a point cloud clustering algorithm and considering the location and sun elevation. The tree stem shadows can be classified with high reliability, as the U-Net classification yields an overall accuracy of 98.6% and an F1-score of 84.4%. Automatically derived DBH values using the proposed method are compared to in-situ values, resulting in a mean error of -1.52 cm and an RMSE of 17.6 cm. In total, DBH values for 26.1% of the overstory trees can be determined. These values also reflect the challenges posed by a dense and multi-layer forest structure, resulting in overlapping and obstructed cast shadows. It is demonstrated that automated derivation of DBH values using cast shadows from UAV-SfM data is feasible, although limited by the density and diversity of the forest stand.

Monitoring Fire and Drought Risk using a Real-time Fuel Moisture System

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Changes in climate will increase wildfire danger and vegetative drought stress across the globe. To be prepared, we need accurate data on live fuel moisture (moisture content within living vegetation). This simple metric is critical for risk management, providing information on how likely and vigorously a fire will spread and identifying areas of low ecosystem resilience where drought-stressed vegetation is more susceptible to additional stressors such as insects and disease. The challenge: fuel moisture has high spatial and temporal heterogeneity, and it is critical to know the fuel type (e.g., grass, scrub, forest, urban) to understand fuel moisture implications.

While scientists have been using remote sensing to evaluate fuel characteristics since the 1980s, rapid improvements in satellite technology combined with increased data cadence provide new opportunities. Many past studies have lacked appropriately scaled calibration and validation data that can quantify moisture across a vertical profile from the upper canopy to the surface fuels. This is partially due to remotely sensed fuel moisture historically being done in isolation without up-to-date spatial characterisation of the fuel type. Without fuel type, fuel moisture is limited in its value: for example, grassland fuel moisture will translate differently to fire behaviour and drought pressure compared to forest fuel moisture.

Remote sensing can evaluate live fuel moisture through satellite and satellite-derived metrics. A real-time fuel moisture system will improve risk management, reducing catastrophic impacts from wildfires and drought. As a stand-alone, real-time fuel moisture provides a critical tool for identifying drought anomalies. Linking real-time live fuel moisture directly to fire behaviour models exponentially increases their value by improving model predictions and risk management. At the simplest level, as vegetation dries out, it burns better. While this is an important indicator for fire behaviour, many fire behaviour models, including NZ models, only consider surface fuel (litter, sticks, twigs, soil) moisture as model input. Surface fuel moisture misses how the fire moves through mixed live and dead vegetation.

Our solution is to use remote sensing to couple real-time fuel moisture with fuel type. We are working towards achieving this through a multi-phase process collaborative project between Scion, NASA Ames Research Center, Australian National University, The US Forest Service and Fire and Emergency NZ. We will present our progress in Phase 1 of - the publication of a roadmap that will identify the developmental pathway of a real-time fuel moisture system. The roadmap is an up-to-date synthesis of what satellite imagery (e.g. Landsat, Sentinel) and remote sensing metrics (e.g. NDVI, NDWI) have been used for evaluating fuel moisture and fuel type in other regions of the world (e.g. Europe, Western North America, Australia). This systematic study provides an understanding of the current state of knowledge and identifies an actionable plan that lays out a strategy to develop a real-time fuel moisture system (Phase 2) and then to couple the system with fire behaviour models (Phase 3).

Using Machine Learning to Upscale ALS derived Forest Structural information

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We present a novel machine learning approach designed to expand the coverage of structural forest datasets derived from Airborne Laser Scanning (ALS). Despite ALS's status as the benchmark for structural forest assessment, its widespread use is hampered by high costs and extensive processing needs. Our workflow integrates ALS with multispectral aerial imagery from the US National Imagery Program (NAIP) to produce a contiguous, landscape-level, 0.5 m synthetic Canopy Height Model (CHM) for the Lake Tahoe Basin. The model utilises a U-Net architecture to predict forest structure beyond the limits of existing ALS data. The upscaling technique produces a sub-meter resolution canopy height model, enabling the pairing of individual, crown dominant trees for validation purposes. We have been using the tree-matching validation technique in a first instance to optimise the point cloud processing against a stem map field survey and its second instance to correlate ALS CHM with synthetic CHM outputs. Derived products such as canopy cover maps show high overall accuracy (≥ 0.82) when compared to ALS products across all tested study sites. The workflow offers a highly scalable solution, working across the heterogenous US Geological Survey ALS database using entirely open-source tools. By aligning with NAIP's biennial updates, our model supports ongoing forest management and carbon sequestration efforts, demonstrating significant potential for landscape-scale environmental monitoring. The further development of this tool has been supported by the MBIE Catalyst program.

Individual Tree Level AGB Model for Different Tree Species based on UAV LiDAR

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Introduction/Aim:
Accurate forest AGB estimation is the primary approach to quantify carbon stocks and sequestration rates. LiDAR signals can penetrate the forest canopy to obtain three-dimensional structural information from the top to the bottom of the forest, which benefit to understand the carbon sequestration capacity of forest ecosystems. Traditional forest AGB inversion methods based on LiDAR technology often requires setting up a large number of field sample plots, and it is difficult to obtain AGB results at the individual tree level. The LiDAR Biomass Index (LBI) has been proved to be able to complete accurate AGB estimation at individual tree level based on the crown size and tree height parameters obtained from terrestrial and airborne laser scanning data. More importantly, only a small number of sample trees were required to achieve model calibration of a certain tree species.

Methods:
Unmanned Aerial Vehicle (UAV) LiDAR technology has the advantages of high accuracy, portability, and low cost, and has gradually become a commonly used data acquisition method in forest survey. This study aims to construct individual tree level AGB models for different tree species and tree species groups based on UAV LiDAR data, and verify their accuracy for further application. Firstly, 10 major coniferous and broad-leaved tree species around worldwide are selected, and the UAV LiDAR data of these tree species are acquired or collected. Secondly, the LiDAR data are segmented into individual trees and matched with field measurement data. Based on the matching results, a small number (≥30) of sample trees with different diameter classes for each tree species were selected. The LBI and tree height parameters of the sample trees are calculated based on the LiDAR data, and the AGB models for different tree species at individual tree level are constructed and verified in combination with the measured AGB. Then, the transferability between biomass models of similar tree species was evaluated and high-precision modelling methods for tree species groups are explored combine with the geometric characteristics of tree species.

Results:
The results indicate that LBI calculated from UAV LiDAR data can be used to construct the individual tree level AGB models for the 10 tree species (The R^2 of AGB models for different tree species range from 0.82 to 0.90). When selected individual trees to validate the accuracy of each model, the values of R^2 are between 0.72 and 0.88 and RMSE are between 45.32 kg and 282.90 kg for different tree species. Meanwhile, the biomass models have a certain degree of universality among tree species with similar geometric features, thereby obtaining acceptable modelling accuracy for tree species groups.

Conclusion:
The results of this study demonstrate the high accuracy and stability of LBI obtained from UAV LiDAR for individual tree level biomass calculation of different tree species, which providing a new method for biomass calculation.

Mapping Forest Height and Biomass change with Time series of ICESat-2 and Optical data: Why we need a time series of Satellite Lidar.

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The first forest height and biomass products using GEDI and ICESat-2 started flowing around 2020, and often fusion of these satellite lidar data streams and optical time series (e.g. from Landsat) were used to estimate past biomass dynamics. Now, in 2024, we have a few years of lidar from GEDI and ICESat-2 and thus have an unprecedented opportunity to assess the accuracy of these past approaches. How sensitive are lidar-optical fusion methods to changes in forest structure? Can they be used to accurately predict loss associated with degradation, such as logging or fire? This research will present early results from validating a time series of lidar-optical fusion with repeat lidar measurements from ICESat-2 between 2019-2023 in boreal forests to determine the relative strengths and limitations of this approach.

Models and maps were developed representing 2020 forest height and biomass conditions across the full boreal domain. These were developed using a high-resolution ICESat-2 ATL08 product (30 m sampling) in combination with wall-to-wall covariate stacks from Landsat, Sentinel-2, the Copernicus DEM and ESA worldcover. These spatial covariates can be mapped annually. This research applied the 2020 lidar model to covariate data from 2023 to estimate change, representative of a typical lidar-optical fusion approach for change mapping. A second approach used ICESat-2 data from 2023 to create a new 2023 model which is presumably more accurate of 2023 conditions. Differences between the two approaches illuminate the limitations of optical-lidar fusion. Often, spectral recovery (e.g. post fire) occurs much more rapidly than structural recovery (height, biomass) and thus traditional optical-lidar approaches likely overestimated the speed of ecosystem recovery from degradation, and underestimate associated biomass losses. Our preliminary results support the need for a continuous time series of satellite lidar, and call for new lidar missions to follow GEDI and ICESat-2 post 2030.

The Future of High-resolution Vegetation Structure mapping for Strategic Forest Inventory Applications – on-going developments in the United States

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Introduction/Aim: Efforts to integrate high-resolution imagery and inventory plots aim to enhance carbon, biomass, and volume estimation at finer scales, specifically within county and national forest contexts. However, dealing with diverse data sources, including varying collection dates, specifications, sensor types, and post-processing methods, poses significant challenges for modelling and inference within a statistically designed annualized plot network.

Methods – status of current systems:
In 2024 a few systems became available to the agency. The US Forest Service in cooperation with USGS and USDA have invested in Imagery Data Manager (IDM) which was developed to process and store UAS data in a cloud environment. Also developed was the Interagency Imagery Publication Platform (IIPP) to store the National Agriculture Imagery Program (NAIP) 2D orthorectified imagery for multiple agencies in a cloud environment. The USFS funded the development of Silvimetric (Hobu, Inc.), which is an app to facilitate the storing and processing of lidar imagery in a cloud environment. The Forest Inventory and Analysis unit extracted temporally relevant lidar imagery over perturbed Nationwide Forest Inventory (NFI) plots to aid in future investigations. Core metrics were extracted. An analysis of these systems and procedures was attempted to illustrate the advantages and disadvantages in producing viable products.

Results:
A synthesis review of different systems sheds light on the advantages and disadvantages of the various platforms and evaluated against core product generation. The incorporation of a comprehensive state-wide data collect can allow for a uniform product in generating a more uniform analytical dataset.

Conclusion:
On-going investigations will lead to a better strategy to incorporate storage, processing, forest tree metrics, and NFI for nationally consistent, localized coverage.

Detecting the Short-Term Effects of Water Stress on Radiata Pine Physiology Using Thermal Imagery

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Several research works had been conducted to characterize the impacts of water stress on plant physiology using thermal imagery [1-5]. However, limited studies had been undertaken specifically on plantation-grown conifers such as radiata pine [6-8]. In this study, thermal imagery has been utilized to determine the impact of short-term water stress in key physiological traits of radiata pine. This had been carried out via collection of canopy level thermal images using FLIR A655SC and GFS-3000 measurements of leaf stomatal conductance (g_s), transpiration rate (E), and assimilation rate (A) from a pot trial where water was withheld from radiata pine over a nine-day period. Results show a consistently high volumetric water content in the well-watered control treatment over the course of the experiment (0.47–0.48 m^3 m^{-3}) but a rapid decline from 0.47 m^3 m^{-3} at 0 days after treatment (DAT) to 0.04 m^3 m^{-3} at 9 DAT in water-stressed radiata pine. No significant differences in the physiological traits were observed for the control and water-stressed groups at 0 DAT. However, by 1 DAT, significant differences in physiological traits between the two groups were apparent, and these differences continued diverging with values in the control treatment exceeding those of trees in the water stress treatment at 9 DAT by 42, 43 and 61%, respectively, for g_s, E and A. Furthermore, the relationships between the normalized canopy temperature, defined as canopy temperature - air temperature (T_c-T_a), and the three physiological traits were highly significant as early as 1 DAT onwards. The strength of the relationships between T_c–T_a and the three physiological traits increased markedly over the duration of the water stress treatment, reaching a maximum coefficient of determination (R^2) at 7 DAT when values were, respectively, 0.87, 0.86 and 0.67 for gs, E and A. The early detection of changes in tree physiology from 1 DAT onwards suggests that thermal imagery may be useful for a range of applications in field-grown radiata pine such as the detection of water stress and identification of drought-tolerant radiata pine genotypes.

Keywords: drought; normalised canopy temperature; Pinus radiata; thermal imagery; radiata pine; water stress

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Extension of GEDI canopy structure with radar and optical imagery for quantifying disturbance effects in an African savanna

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The savanna of South Africa's Kruger National Park and surrounding landscapes are subject to a multitude of disturbance pressures such as from megafauna and timber and fuelwood harvesting. Airborne lidar and its fusion with satellite imaging has proven effective in quantifying woody vegetation structure and the effects of disturbances in small locales of this region. However, the limited spatial coverage of airborne lidar precludes its use for calibrating models that apply to the diversity of vegetation types across the Greater Kruger region. Spaceborne waveform lidar from the Global Ecosystem Dynamics Instrument (GEDI) provides an alternative for measurements of canopy structure that can be extended wall-to-wall through fusion with other remote sensing datasets. We compared methods for annual mapping GEDI's relative height 98th percentile (RH98), foliage height diversity (FHD), plant area index (PAI), and canopy cover (COV) from 2007 to 2023 using different combinations of PALSAR-1/2 backscatter coefficients, Landsat, and phenology metrics derived from Harmonized Landsat Sentinel-2. In initial models, joint Landsat and PALSAR predictors yield slightly higher accuracies (e.g., RH98 RMSE = 4.6%, R^2 = 0.46) than either Landsat (RH98 RMSE = 4.8%, R^2 = 0.43) or PALSAR (RH98 RMSE = 5.3%, R^2 = 0.3) alone. The temporal transferability of these different models and resulting maps were evaluated against withheld years of GEDI data using temporal cross-validation with small area estimation to test their suitability for use in years outside the range of GEDI data collection. The highest performing model was then used in model-based estimators to quantify changes in canopy structure for areas experiencing recent land management and land use changes such as timber harvesting in communal lands and elephant impacts following fence removal for private nature reserves.

The influence of reference source on tree canopy cover mapping and post-stratified estimation of forest structure in Colorado

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Remotely sensed fractional tree canopy cover has proven useful in a wide range of environmental applications, including carbon monitoring. For example, the US Forest Inventory and Analysis (FIA) program uses the Tree Canopy Cover product from the National Land Cover Database for post-stratified estimation of aboveground biomass and other forest structure attributes at county, state, and national levels. However, generation and validation of canopy cover maps across broad spatiotemporal extents is challenging due to the limited availability of consistent reference measurements. Using new canopy cover references sources and combining different reference sources could provide greater spatiotemporal coverage to support map generation, but the disparate measurement approaches between reference sources may affect their suitability for combination and their individual effectiveness in particular applications. We tested the use of multiple reference sources alone and in select combinations for generating annual wall-to-wall canopy cover maps using temporally fitted Landsat time series processed with the LandTrendr algorithm. These reference sources include aerial photo-interpretation with a dot-grid, field line transects, estimates based on stem-to-crown allometry, and spaceborne and airborne lidar. The maps derived from each data source or combination were compared by their Landsat model accuracy and their accuracy according to airborne lidar maps of canopy cover. Each of the canopy cover maps were then used for stratifying FIA plots in post-stratified estimation of county- and state-level forest aboveground biomass. Initial results show that Landsat-based models of the canopy cover sources have similar accuracy when considering the full range of canopy cover (airborne lidar RMSE=9.2% to spaceborne lidar RMSE=13.3%), which is in part because of zero-inflation across all datasets. When considering only forest areas (i.e., canopy cover ≥10%), the range in Landsat model accuracy was much wider (stem-allometry method RMSE = 12.8%; spaceborne lidar RMSE=23%). Airborne lidar and stem-mapped estimates were similar where coincident (r=0.86), and combining these datasets slightly improved Landsat model accuracy (overall RMSE=9.0%; forest RMSE= 12.3%). All analyses were conducted in Colorado forests, where we further explored accuracy and biases across forest types and cover levels. Understanding which reference sources could be complimentary and which have the strongest relationship with Landsat imagery provides insights for improving broad-scale mapping of tree canopy cover and its influence on subsequent forest structure estimation and carbon monitoring.

Automated Georectification, Mosaicking and 3D Hyperspectral Point Cloud Generation

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Introduction/Aim:

Hyperspectral sensors mounted on unmanned aerial vehicles (UAV) allow high-resolution multi-temporal spectral analysis for a range of remote sensing applications. However, although accurate onboard navigation sensors track the moment-to-moment pose of the UAV in flight, geometric distortions are introduced into the hyperspectral data cubes. Consequently, considerable time-consuming (user/manual) post-processing rectification effort is generally required to retrieve geometrically accurate mosaics of the scanned data sets. Moreover, due to the line-scan nature of many hyperspectral sensors and users are unable to exploit structure from motion (SfM) techniques, so only 2D mosaics are created.

Methods:

To address this, we propose a fast, automated and computationally robust georectification and mosaicking technique that also generates 3D hyperspectral point clouds. The technique first morphologically and geometrically examines (and, if possible, repairs) poorly constructed individual hyperspectral cubes before aligning these cubes into swaths. The luminance of each individual cube is estimated and normalised, prior being integrated into a swath of images. The hyperspectral swaths are co-registered to a targeted element of a luminance-normalised orthomosaic obtained using a standard red-green-blue (RGB) camera and SfM. To avoid computationally intensive image processing operations such as 2D convolutions, key elements of the orthomosaic are identified using pixel masks, pixel index manipulation and nearest neighbour searches. Maximally Stable Extremal Regions (MSER) and Speeded-Up Robust Feature (SURF) extraction are then combined with Maximum Likelihood Sample Consensus (MLESAC) feature matching to generate the best geo-metric transformation model for each swath. This geometrically transforms and merges individual push-broom scanlines into a single spatially continuous hyperspectral mosaic; and this geo-rectified 2D hyperspectral mosaic is then converted into a 3D hyperspectral point cloud by aligning the hyperspectral mosaic with the RGB point cloud used to create the orthomosaic obtained using SfM.

Results:

High spatial accuracy is demonstrated. Hyperspectral mosaics with 5cm spatial resolution were mosaicked with root mean square positional accuracies of 0.42 m. The technique was tested on five scenes comprising two types of landscape. The entire process, which is coded in MATLAB, takes around twenty minutes to process data sets covering around 30Ha at 5cm resolution on a laptop with 32GB RAM and an Intel® Core i7-8850H CPU running at 2.60GHz.

PINT – A Program for Performing Survival Counts

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Introduction/Aim:
Seedlings represent an acutely vulnerable stage of a tree's development cycle. Field surveys have historically been used to assess survival: a practice that is costly and not without hazard. It is also challenging to tackle the problem operationally or at scale using remote sensing due to a combination of the diminutive size of young trees, absence of distinctive morphological structure, and quantity of data involved. Moreover, monitoring needs can be site-specific and influenced by factors such as plant maturity, local vegetation, substrate, and geomorphology. Successful techniques for conifer seedling detection based on supervised and deep learning have been reported; and while these methods claim precision rates in excess of 80% and accuracy in excess of 90%, such approaches rely on convolution neural networks (CNN), which require extensive training data sets.

In this paper we discuss an approach based on morphological and spatial filtering that automatically detects healthy young pinus radiata and eucalyptus seedlings in plantations. The likely locations of individual unhealthy or deceased ("missing") trees are also computed based on the non-uniform distributions of identified healthy trees.

Methods:
The strategy adopted is as follows. Standard flight patterns are flown by an unmanned aerial vehicle and a 3D point cloud created from the 2D image stack using standard photogrammetric software. The 3D point cloud is normalised to the topography of the local terrain and a series of morphological operations used to provide additional properties for points identified as connected identities. Unwanted points are discarded, and the residual data morphologically and spatially filtered using seedling colour, structure, and distribution. Maps of the resulting entities are computed and used to represent the locations of healthy seedlings. Based on the estimated probability distributions of the identified trees, locations of missing trees are then inferred, which allows tree density and replenishment diagrams to be created as a function of site geography. Weeds are also detected and classified by type.

Results:
Diagnostic tests conducted on over 2,000 Ha of radiata pine and eucalyptus plantation show that the proposed approach allows healthy trees to be detected and located both reliably and accurately, and that the likelihood of falsely identifying unhealthy trees is low (< 5%). The healthy seedling classification algorithm demonstrated precision and specificity in the region of 90 – 95%, and recall approaching 99%, with about 85% of missing/unhealthy seedlings shown to have been located within 1 m of their correct position. Weed detection and classification was similarly successful.

Conclusion:
This approach will allow practitioners to estimate reforestation costs more efficiently and inexpensively. It offers forestry practitioners a monitoring solution that is fine-resolution, rapid and scalable and supports precision mapping. The method could potentially accelerate the recovery of forest ecosystems with respect to their health, integrity, and sustainability.

On the Value of Aerial and Terrestrial 3D Point Cloud Fusion

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Introduction/Aim:
Over the past decade light detection and ranging (LiDAR) technology has become a dominant remote sensing tool for modelling and monitoring forest attributes. It is used by both forest managers and researchers and may be deployed aerially (on manned or unmanned platforms) and terrestrially. The 3D point clouds obtained from these instantiations may then be used to model and monitor a range of forest and individual tree properties. Each deployment option enjoys, and suffers from, its own advantages and disadvantages.

In this paper we discuss the value proposition of stand-alone point clouds obtained from modestly priced terrestrial and aerial LiDAR sensors, and the forest attributes derived from them. We also fuse the data from each single source to provide a more complete point cloud and examine the pros and cons of this additional step by measuring the accuracy and efficacy of a range of attributes obtained using standard techniques.

Methods:
Numerous studies have shown that LiDAR-based remote sensing techniques and tools can successfully and cost-effectively model and quantify forest structure at the plot and individual tree levels. For each point cloud (individual and fused), we compare the accuracy and coverage of key attributes like tree height, diameter at breast height, and tree crown metrics (e.g., projection area, width, and volume), which correlate highly to biomass production and carbon sequestration. These are compared to the benchmarked attributes that are measured by hand.

Results:
The density of the aerial point clouds offer advantage above 12 – 15m and in terms of coverage, and most noticeably in terms of canopy modelling and measurement. On the other hand, the terrestrial point clouds offer significantly higher point densities below this height but suffer from coverage deficiencies; and the fused data set is, of course, constrained by the terrestrial coverage. The individual tree attributes obtained using each method, however, offer the opportunity to impute attributes from within the merged sector of the cloud to the aerially observed data set.

Conclusion:
The value of stand-alone aerial and terrestrial LiDAR remote sensing observations are evaluated using several tree metrics for radiata pine. The results indicate fusion from high-performance equipment can improve the 3D mapping of forest structure and thus the modelling and observation of individual tree attributes. Whilst there are research benefits of fusing the point clouds (e.g., in imputation modelling and propagation studies), it is found that this additional step is unlikely to find operational utility for forest managers at present.

Using Aerial Lidar and Mobile Terrestrial GNSS to estimate Signal Attenuation in Foliage

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Using aerial lidar and mobile terrestrial GNSS to estimate signal attenuation in foliage

Predicting the performance of satellite navigation tools in forestry environments requires that the signal propagation characteristics of foliage be known. A study has been undertaken to fuse aerial drone based lidar measurements of forest canopy shape with data from mobile terrestrial GNSS receivers, with the end result being a standardized method for estimating the attenuation coefficient of GNSS signals passing through foliage. Initial results are presented based on a survey of planted radiata pine of two different sizes, which yield estimates of the attenuation coefficient consistent with theoretical predictions.
Estimation of signal attenuation through a volume of foliage mapped with lidar presents a significant choice in how to approach the use of lidar points to model the presence of foliage. The most straightforward approach is to simply voxelize the point cloud by checking each 3-D bin for the presence of lidar return. This, however, assumes that all foliage is accessible to the lidar sensor. In practice, penetration of laser radiation and resultant measurable return decreases with foliage depth. This means that, for dense canopy structures, only the outer portion of forest canopy can be reliably mapped.
Theoretical predictions of signal propagation in forest environments often overcome this limitation by approximating forested areas as homogenous slabs with some vertical variation in the attenuation coefficient. While this is sufficient to model the average attenuation of signals propagation at shallow elevation angles, such as telecommunications, GNSS signals are necessarily spread across a wide range of elevation angles, with individual detection vectors possibly passing through or between canopy foliage, depending on exact location.
A compromise between direct measurement of the entire canopy and an oversimplified slab is therefore introduced. The volume of attenuating foliage is modeled by using lidar data to extract the external envelope of forest canopy, based on the maximum height of lidar return in each horizontal bin. Signals are considered to be travelling through foliage when their propagation vector is within the canopy envelope. Currently this uses only the upper boundary of the canopy, but in future this method can also be used from beneath with terrestrial lidar and combined with aerial data to produce a realistic 3-D volume based on the upper and lower edges of the canopy.
Results are presented from a survey of two regions of planted radiata pine with ages of 10 and 19 years. Canopy volumes inferred from lidar derived external envelopes have been compared with data recorded by a GNSS receiver carried on a traversal that ranged from outside the forested area, along the edge, and inside the interior. Attenuation coefficients were estimated from the observed SNR of each detected satellite at each point along the traversal. Values of the attenuation coefficients produced using this method are consistent with theoretical predictions and other similar studies. It is intended that these results will be the first step in producing more accurate predictive model of GNSS performance for high-precision forestry applications.

Best practice for mapping aboveground carbon in Afrotemperate forests

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Under the Paris Agreement, signatories are obliged to reduce carbon emissions and enhance carbon sinks. Multiple global aboveground biomass products are now available; however, they still require additional calibration and validation datasets at the local scale. I use South Africa’s Afrotemperate forests as a case study to investigate best practice for remote sensing aboveground carbon for improving the accuracy of reporting under the Paris Agreement. I collected both field and LiDAR data for three forests in KwaZulu-Natal, South Africa, and tested three different allometric equations for calculating AGC. I used linear models to predict AGC from LiDAR data for both local and multi-site models and then compared the results with two global biomass products. The locally derived allometric produced intermediate AGC values to the temperate and pan-tropical equations and is recommended for use in South African forests. Local LiDAR models for each forest varied in performance with R^2 values ranging from 0.16 to 0.75, and RMSE% of 7.3 to 50%. Overall, the multi-site LiDAR model performed better than two of the three local models with a conditional pseudo-R^2 of 0.82 and RMSE on 24% (30 $MgC.ha^{-1}$) and is recommended in the absence of field data. However, since the forest physiognomy is diverse, it is important to take local context into account when interpreting AGC results. Although global biomass products tend to overestimate the carbon in these forests, they can still be used for the UNFCCC’s 2023 global carbon stocktake until further calibration and validation data have been included. While generalized mapping techniques may produce some errors in AGC estimates, it's important to use the data that's currently available and report the uncertainty in the estimates as part of mitigating anthropogenic changes.

Comparative Analysis of Leaf Area Index Measurement Methods in a Mixed mid-European Forest

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The Leaf Area Index (LAI) is a critical ecological variable of the canopy structure. It is highly relevant for biomass and carbon estimation as well as for a variety of silvicultural and climate modelling approaches. Accurate LAI measurements are vital for understanding forest health, biodiversity, and productivity. This study focuses on comparing different LAI measurement methods in a 1-hectare mixed forest in Mecklenburg-Western Pomerania, Germany. The forest stand comprises approximately 300 individual trees including European beech (*Fagus sylvatica*), English oak (*Quercus robur*), green Douglas fir (*P. menziesii*), European larch (*Larix decidua*), and Norway spruce (*Picea abies*). Therefore, it provides a complex canopy structure necessary for robustly evaluating LAI measurement techniques.

The objective of our research is to compare different methods for deriving the LAI in terms of accuracy and measurement efficiency. Additionally, we aim to better understand the main differences between single tree and forest stand detection methods, and to explore the possibility of combining various methods for enhanced accuracy.

We utilized a range of instruments and techniques, including Fish-Eye cameras, the LI-COR 2200 Plant Canopy Analyzer, litter traps, the SOL300 Solariscope, Airborne Laser Scanning (ALS), and Terrestrial Laser Scanning (TLS). Data collection occurred during two field campaigns in September 2023 (leaf on) and in March 2024 (leaf off), to capture seasonal variations in LAI and to differentiate between the woody and actual leaf contribution, i.e. Plant Area Index (PAI) vs. LAI.

Preliminary results indicate significant differences in LAI measurements between the methods. Fish-Eye photography, LI-COR 2200, and Solariscope measurements provided quick, efficient and comparable LAI estimates (r^2 between methods of 0.46 to 0.95, depending on measurement angles and linear / non-linear correlation) but varied greatly in accuracy when compared to ground truth measurements obtained through litter traps. The analysis of ALS and TLS data is ongoing and promises high-resolution three-dimensional insights into forest canopy structure.

The comparison between active (e.g., LiDAR-based methods such as ALS and TLS) and passive (e.g., Fish-Eye, LI-COR 2200) LAI measurement techniques reveals relevant differences. Active methods offer detailed three-dimensional representations of canopy structure, potentially providing LAI values for single trees. However, they require sophisticated pre-processing and are resource intensive. Passive methods, while less accurate in complex forest structures, offer efficiency and ease of use. The integration of active and passive methods could potentially offer a robust solution for LAI measurement across different forest types.

Our study contributes to the discussion on the most effective method for measuring LAI in forest ecosystems. The mixed forest in Mecklenburg-Western Pomerania serves as an excellent study area for this comparison, given its diverse species composition and complex canopy structure.

Further analysis is required to refine the comparison of measurement techniques and to explore the potential of method integration. The possible combination of active and passive methods might provide a LAI measurement of high accuracy and efficiency. Our study underscores the importance of selecting appropriate measurement techniques based on forest type and research objectives.

Connecting Fuels and Fuel condition to Site-level Fire Energy Sensing

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Introduction:
Wildland fire behavior and emissions are highly dependent on the type, arrangement, and condition of the fuels that are burning. Fuel conditions are a primary factor in driving fire energy and the progression across the landscape and spread of fire though a site. Additionally, large discrepancies between different model-based estimates of carbon and pollutant production in current smoke emission inventories are the result of broad assumptions regarding what is burning and under what conditions. In this study, we have used advanced in-situ fire energy sensing to consider the influence of fuels on fire energy signatures.

Methods:
We have aggregated fine-scale fuel, consumption, and fire radiative power (FRP) estimates associated with prescribed surface fires to the scale of trees, forest stands, and management units. Radiometry data of active fire was collected at several prescribed burns across the United States (US) coincident with detailed fuels consumption measurements. The data were collected with a variety of nadir-viewing dual-band and five-band radiometers distributed across a statistical sampling of fuel types and densities. The radiometers were calibrated with laboratory blackbody data to derive sensor response models that allowed FRP retrievals. The integrated FRP data was used to derive fuel consumption estimates that were compared with values derived from pre- and post-fire fuels measurements.

Results:
Preliminary results indicate the radiometrically and clip-plot derived fuel consumption estimates often show good agreement, although they are sensitive to the statistical sampling of different fuel sizes and assumptions about the radiative fraction of the total combustion energy. We will discuss complications arising from the fuel sampling procedure and its impact on consumption estimates. We will also describe preliminary attempts to measure convective heat flow co-located with the radiometry measurements, in an attempt to reduce the uncertainties about the total heat budget.

Conclusions:
From local to global scale, remote sensing has become an indispensable tool for monitoring fire and its effects. Connecting remote measurements of fire energy to fuel characteristics provides fundamental data on the influence of fuels and their condition on fire behavior and emissions.

Mapping Circumpolar Fire Emissions for Carbon Cycle Modeling

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Introduction:

Boreal ecosystems occupy 22% of the terrestrial surface and contain more than 40% of the world's soil carbon inventory that is vulnerable to change in near-term climate conditions. Wildfire occurrence has increased in northern high latitudes in recent decades, with an increase in both fire number and burned area. In Siberia alone, the fluctuation of burned area ranged from 3 to 20 million hectares over the last two decades. Concurrently, mean global air temperatures have increased during the last century and the largest temperature increases on Earth are found in circumpolar regions.

For this paper we review development of a circumpolar burn severity product that was used to improve estimates of total carbon exchange using the Wildland Fire Emissions Inventory System (WFEIS) to map direct carbon emissions and the Terrestrial Ecosystem Model (TEM) for long-term carbon exchange. Burn severity is a significant factor for mapping immediate emissions and for improved modeling of post-fire carbon exchange.

Methods and Results:

To adequately quantify the role of boreal forest ecosystems in the global carbon budget, a dataset of spatially and temporally explicit fire burn area with severity was developed for all regions north of 50 deg latitude for 1986-2020 for North America and 2003-2016 for Eurasia (the Eurasia dataset being limited to the MODIS mission). Fire perimeters were compiled from existing fire databases or were derived from Landsat and MODIS and were processed to ensure that they had valid geometry, including repairing perimeter geometries and simplifying geometry to a 60 meter resolution to improve processing time. Burn severity was determined from Landsat TM/ETM+ by assigning pre- and post-Normalized Burn Ratio (NBR) values within each fire perimeter and calculating adjusted dNBR and RdNBR. Uncertainty associated with remote sensing of burn severity and fire perimeter estimation is a consideration for accounting fire emissions and post-fire carbon exchange. In this work we provide a summary of the contributing sources of error in burn severity estimation and evaluate our burn area products for this error.

This dataset was then used in evaluation of the role of severity in post-fire carbon exchange, and assessment of circumpolar fire distribution and trends in burn area, severity, and ecoregion. Results show an increase in regional burn severities during the study period and that severity is a factor in both immediate and long-term carbon exchange.

Next Generation Landsat Satellites for Forestry Applications

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Landsat satellites have been providing continuous monitoring of the Earth's surface since 1972. Landsat satellites provide multispectral imagery to help land managers and policy makers make informed decisions about natural resources and the environment. Data acquired by Landsat satellites support scientific research across many disciplines including agriculture, forestry, land cover/use, water quality, carbon storage, disaster response, energy and minerals, and climate change. Landsat data is crucial for forest management and is widely used for forest fragmentation detection, forest health monitoring, fire management, and land use transition research at local, regional, national, and global scales. The free and open data policy of the Landsat program enables the global land imaging user community to explore the entire 51-year long-term data record to advance our scientific knowledge and explore innovative use of remote sensing data to support a variety of forestry applications. To ensure continuity of Landsat data and enhance Landsat's ability to meet evolving user needs, the planning for the follow-on mission, Landsat Next is underway. The US Geological Survey (USGS) reached out to a broad Federal civil land imaging research and operational user community to understand their satellite-based imagery applications and needs. The user community expressed interest in improving the spatial resolution, temporal revisit, spectral coverage, and coordination with international missions while maintaining the data quality and compatibility with the Landsat archive. This presentation will provide an overview of the Landsat user engagement activities, Landsat Next science requirements and mission architecture, and efforts to enhance forest observation and analysis capabilities through new sensors and remote sensing technology.

Multitemporal Multispectral UAV, Ecophysiology, and Genetic Data for monitoring Forest Dieback in Remote-Abyssal Beech Population

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Introduction/Aim:
In the context of climate change, forest tree populations extending beyond the continuous distribution range of the species, which serve as vital biodiversity hotspots, require intensive monitoring. This is particularly crucial due to the escalating impact of heatwaves and droughts, notably in the Mediterranean region.
In Italy, beech populations are facing significant challenges due to increasing heatwaves, droughts, and the fungus Biscogniauxia nummularia (Bull.) Kuntze. This fungus, an endophyte and opportunistic pathogen, is now emerging as the agent of charcoal canker disease, potentially threatening the conservation of small, disjunct and heterotopic populations. Aabyssal beech population is in 60 ha of the Castelvecchio Natural Reserve (Italy) and is vital biodiversity hotspots protected under the EU Natura 2000. Continuous monitoring of this type of beech forests is essential to understand the dynamics of the dieback and identify resilient plants.

Methods:
Directly monitoring all trees on the ground within the forest area is unfeasible. Thus, we implemented continuous monitoring of beech populations at low altitude by acquiring diverse data types, including: (i) tree health data at tree level, entailing the estimation of leaf chlorophyll content (Chl) using SPAD-502-Plus , (ii) genetic data at tree level using buds, and (iii) multispectral data capturing the entire area using a Micasense RedEdge-M camera mounted on a WINGTRA ONE fixed-wing UAV. To establish monitoring, each tree sampled on the ground for health status and genetic data was geolocated using a topographic GNSS receiver to correlate tree vitality data with UAV multispectral data. Two field campaigns were conducted one year apart in June/July, coinciding with the full leaf development period of beech trees. UAV multispectral data were processed, and orthomosaics were used to segment the crowns and calculate vegetation indices. Specifically, the RedEdge band was utilized to segment the crowns within the entire area using a Simple Linear Iterative Clustering algorithm (SLIC), and for each segmented crown, the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Red Edge Index (NDRE) were calculated at a spatial resolution of 10 cm.

Results:
Overall, most sampled trees exhibited good canopy functionality, with Chl values ranging between 30 and 43, and NDVI and NDRE values ranging between 0.8 - 0.9 and 0.4 - 0.5 respectively. The results displayed significant correlation between NDRE and chlorophyll ($r = 0.77$; $p=0.009$) for sampled trees, while no significant correlation was found with NDVI ($r=0.58$, $p>0.1$), indicating the effectiveness of the NDRE index in estimating chlorophyll content, while NDVI seems to saturate. Utilizing the correlation results and segmented tree crowns, a threshold approach calibrated using NDRE and Chl enabled the mapping of tree dieback within the area and within each crown, indicating varying levels of dieback, such as dead canopy, stressed canopy, and healthy canopy.

Conclusion:
The second field campaign facilitated monitoring the dynamic of dieback within the populations and within each crown, aiding in the identification of beech trees more suited for gene conservation due to their enhanced resistance. Additionally, the analysis of dynamics allowed for the examination of environmental factors influencing the phenomenon, such as the scarcity of affected plants along drainage lines compared to other areas.

Estimating Canopy and Stand structure in Hybrid Poplar Plantations combining Digital Terrestrial Photography and Multispectral UAV Imagery.

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Introduction/Aim:
In today's context, the adoption of precision forestry tools for managing poplar plantations is highly desirable (Corona et al., 2022; Fardusi et al., 2017). These new instruments offer the potential to update and develop advanced monitoring systems, providing precise estimation of various poplar variables at both stand and tree levels (Dash et al., 2016; Fardusi et al., 2017; Puletti et al., 2019). In fact, timely and accurate monitoring of poplar plantations is essential (Cantamessa et al., 2022; Meroni et al., 2004; Pu et al., 2021). Among the various poplar plantation variables, precise estimates of canopy characteristics such as canopy cover (CC), Leaf Area Index (LAI), and Crown Volume (Vcr) are of fundamental importance for effective poplar plantation management. These variables have a direct impact on the growth rate and the occurrence of poplar stress (Gago et al., 2015; Li et al., 2023).

Methods:
In this study, we examined the use of multispectral photogrammetric data collected via UAVs with a Micasense RedEdge camera for the retrieval of canopy and stand attributes within hybrid poplar plantations, developing a methodology that integrates terrestrial digital photos to predict the above-mentioned variables.
Terrestrial digital photography was used at the plot level to acquire digital cover photography (DCP) images (Macfarlane et al., 2007) under overcast sky conditions along a grid of 16 sampling points using a digital single-lens reflex camera (Nikon D90) fitted with an AF Nikkor 50mm 1:1.8 D fixed lens, which yields a field of view of about 30°. From DCP, we calculated the canopy variables: CC, LAI, and Vcr. The multispectral UAV orthomosaic was instead used to segment the single crown of the poplar plantation using the RedEdge band and a Simple Linear Iterative Clustering (SLIC) algorithm. Based on the segmented tree crowns, the Grey Level Co-occurrence Matrix (GLCM) was calculated for each crown based on different spectral bands and used to predict the canopy variables at the single tree level.

Results:
The accuracy was calculated based on an independent dataset, and the results showed a significant correlation between predicted and measured values of the considered poplar plantation variables (i.e., Vcr, CC, and LAI) with R^2 consistently higher or equal to 0.86 (R2 val.) for all the tested models. The most accurate predictions for LAI and CC were achieved using GLCM variance calculated on the RedEdge band, while GLCM entropy calculated on the base of the NIR band performed for Vcr. The MAE and the RMSE are generally consistent with the standard deviations of the observed values for all the variables (Vcr = 131.2; CC = 0.23; LAI = 0.64).

Conclusion:
This research underscores the importance of GLCM texture metrics derived from multispectral UAV orthomosaic as significant explanatory variables for accurately predicting poplar plantation canopy characteristics. The results of this study suggest that the proposed approach provides a dependable and efficient alternative to traditional measurement techniques, necessitating only a limited number of field plot acquisitions. Additionally, the use of DPC also reduces the time required for plot acquisition compared to extensive traditional field campaigns.

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Assessing the potential of ICESat-2 data to retrieve fuel-related variables

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Introduction/Aim:
Recent studies suggest that fire regimes will be altered in response to climate change, leading to increased frequency and intensity of wildfires in fire-prone areas, as well as expansion into previously unaffected regions. In the Mediterranean region, projected weather conditions, combined with existing vegetation patterns, are expected to contribute to more frequent and severe wildfires. Portugal has already experienced catastrophic consequences of these extreme circumstances in 2003, 2005, and 2017, with large wildfires causing extensive economic, environmental, and human losses.

The characterization and mapping of fuels are recognized as critical factors in wildfire prevention and planning. Fuel management is a direct method for reducing fire risk, and fire behavior simulators (e.g., FARSITE, FlamMap) are valuable tools for supporting fire and fuel management decisions. However, the accuracy of simulation outputs depends heavily on the availability of precise fuel data. High-quality information on variables such as canopy height (CH), canopy cover (CC), canopy base height (CBH), canopy bulk density (CBD), and canopy fuel load (CFL) is essential for accurate wildfire management decisions.

The overarching objective of this study had two main components: i) evaluating the utility of ICESat-2 data for estimating key fuel-related variables, and ii) creating a comprehensive map of these variables at a 25-meter resolution by integrating ICESat-2 data with other remotely sensed datasets such as Sentinel-1, Sentinel-2, ALOS2/PALSAR2, and SRTM.

To achieve the first goal, a three-step approach was implemented: (i) modeling fuel-related variables using field-based vegetation measurements and ALS-derived metrics; (ii) generating ALS-based estimates of key fuel-related variables to provide ground-truth information across the study area; and (iii) assessing the utility of ICESat-2 ATL08 canopy height and cover metrics for estimating key fuel-related variables. An error analysis regarding the ICESat-2 derived estimates for the key fuel-related variables and the ICESat-2 standard CH estimates was performed to understand how different factors (e.g. land cover type, canopy cover, and slope) could affect the performance of the estimates. For the second objective, the Google Earth Engine cloud-computing platform was used to preprocess, mosaic, and retrieve Sentinel-1, Sentinel-2, PALSAR-2, and topographical data. Additionally, it was utilized to compute a suite of vegetation indices and textural metrics (GLCM). The Random Forest machine learning algorithm was then applied to predict each of the fuel-related variables using the aforementioned multisource satellite data.

In this presentation, we will discuss the primary strengths and limitations of ICESat-2 data in providing useful and accurate information about key fuel-related metrics in a semi-arid Mediterranean landscape.

Climatic-induced mangrove dieback in the Gulf of Carpentaria, Australia

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Mangrove ecosystems are being lost largely due to human activities and the increasing effects of climate change. Recent research has proposed that changes in mangrove distribution and events of mangrove dieback will become more frequent and intense.
However, a lack of detailed, long-term monitoring using Earth observation data has limited our understanding of the specific impacts of climatic events like El Niño-Southern Oscillation (ENSO) on mangrove structure and condition. Changes in mangrove vegetation dynamics was assessed on a large scale for each year between 1987 and 2023, focussing initially on the Leichhardt River region, and later expanded to include other regions of the Gulf of Carpentaria (GoC), an area minimally influenced by human intervention. We used a combination of remote sensing data from Landsat 5, 7, and 8 retrieved from Digital Earth Australia (DEA), with ancillary sources such as LiDAR and aerial photography to differentiate mangrove zones and areas of mangrove dieback. These zones represent distinct mangrove ecosystems and included a *Rhizophora*-dominated zone, open and closed *Avicennia*-dominated zones, and open and closed mixed zones. We accessed changes in mangrove conditions, including greenness, vegetation moisture content and canopy structure, for each zone using NDVI, NDWI and Fractional Vegetation Cover (FVC), respectively. We used climate data indicators reporting changes in temperature, precipitation, and sea level, such as Southern Oscillation Index (SOI), Dipole Mode Index (DMI), and Lunar Nodal Cycle (LNC) to identify climate anomalies affecting mangroves. Overall, the mangrove zones classification (kappa = 0.84) showed closed vegetation zones expanding in area over the years, while open areas tend to be more stable in the region. The co-occurrence of different climatic and tidal perturbations, including ENSO, Indian Ocan Dipole (IOD) and LNC, in the 1990's and 2015/2016 contributed to higher mangrove dieback extent and pronounced declining conditions for all the zones, with major effects at higher elevations in the tidal frame. Early signs of mangrove dieback were observed prior to the 2015/2016 ENSO event as declining conditions in NDVI and NDWI. By integrating estimates of mangrove zones extent over time with climate analyses and assessments of condition, this study offers novel insights into the temporal and spatial dynamics of mangrove ecosystems. This research elucidates the mangrove response mechanisms to environmental change and offer an approach to monitoring and managing these areas in the face of climate uncertainty.

Precision Silviculture: Real-Time Thinning Assessment

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Abstract: This project introduces a real-time thinning assessment tool for forestry silviculture, utilizing UAVs and deep learning. The tool is capable of analysing tree density, species composition, and environmental factors from various data sources, including pictures, videos, and streams. Additionally, it provides tree detection results and stocking information.

Introduction: The study reviews existing literature on tree counting and detection through remote sensing techniques and deep neural networks, identifying a gap in convenient and practical tree-counting software. The aim and scope of the project are to develop an intelligent tree-counting software for real-time thinning assessment.

Methods: The project comprises three main phases: data collection and labelling, model training, and software development.

Data Collection and Labelling: The optimal drone settings for image capture are determined, and data are collected from four different forests with varying ages and thinning conditions. A total of 25,794 instances are labelled across 80 images using an open-source library and model-assisting annotation pipeline.

Model Training: YOLOv8-m is selected as the target model due to its balance between accuracy and speed. The model is trained on 58 labelled images for training and 14 for validation, with testing conducted on 8 labelled images from a post-thinning block. Performance metrics such as precision, recall, and mean average precision are reported.

Software Development: A user-friendly software compatible with Windows operating systems is developed utilizing the OpenCV DNN module and CPU for inference. The software offers three branches for picture, video, and stream inference, providing tree detection results and stocking information.

Results: The trained model achieves a mean average precision of 84% on the validation dataset and 92.5% on the testing dataset. The software demonstrates high accuracy and speed in real-time thinning assessment across various data types, with the capability to save inference results for further analysis.

Conclusion: This project introduces a prototype tree-counting tool capable of providing real-time feedback on thinning operations, facilitating more efficient and informed decision-making for forestry managers. While the tool exhibits limitations such as model performance stability, drone platform, and output format, future work aims to address these issues and enhance the tool's functionality.

Estimation of Above-Ground Biomass in Forested Areas of Hawaii and Spain Using Small Area Estimation with LiDAR Auxiliary Information and GEDI

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Introduction/Aim:
Stand exams and field plots with low positional accuracies are commonplace in informing forest management operations, yet they are underused in remote sensing analyses. Area-level models, allow combining remote sensing data with this kind of observations to estimate forest attributes for stands and management units of similar size. LiDAR data have been used in operational forest inventories for over a decade (Mauro et al., 2017) and the Global Ecosystem Dynamics Investigation (GEDI) spaceborne sensor provides auxiliary information that can be used with field plots with low positional accuracy to fit area-level models (Hunka et al., 2023). This study compares direct estimators of Above Ground Biomass (AGB) with no auxiliary information to area-level EBLUPs using LiDAR and GEDI auxiliary information.

Methods:
Comparisons were conducted in pine-dominated forests in Spain and eucalyptus-dominated forests in Hawaii—comprising 23 and 62 management units and 140 and 150 ground plots. To assess the performance of each method, root mean squared errors for stand-level estimates were compared.

Results:
Preliminary findings suggest that direct field estimates have larger RMSEs than area-level EBLUPs based on either LiDAR auxiliary information. In Spain, field estimates demonstrated the highest level of uncertainty, with relative errors reaching 27.09%, in contrast to the 9.77% relative errors obtained using the small area estimation method. Consequently, area-level EBLUPs improve accuracy over direct estimates. This enhancement is particularly valuable considering the modest cost of getting low-precision field plot coordinates. Results referring to the use of GEDI as a supplementary source to field data remain inconclusive at this stage. These results have important applications in operational settings, demonstrating that existing databases of field plots with low positional accuracy, can still play an important role when combined with remote sensing data.

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Exploring Queensland's Woody Landscape: Structural Insights from GEDI LiDAR

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Introduction/Aim:
There is significant public, state, national and international interest in deforestation to inform climate and emission policy and reporting, biodiversity conservation, nature-positive outcomes, and supply chain policies related to environmental, social and governance (ESG). Mapping deforestation remains a challenge – all current forest definitions incorporate a height threshold that is not easy to measure and monitor on-ground or from passive remote sensing optical data. The Queensland State Government has a robust and spatially-comprehensive woody vegetation mapping and monitoring program in the Statewide Land and Trees Study (SLATS). However, SLATS is deliberately agnostic to forest definitions, mainly because it does not presently quantify height. New active remote sensing technologies, such as spaceborne LiDAR, have the potential to inform monitoring and reporting of deforestation against national and international definitions within Queensland. This study aims to place the SLATS woody extent data product in the context of national and international definitions of forest through the integration of the Global Ecosystem Dynamics Investigation (GEDI) spaceborne LiDAR data. Furthermore, by characterising the SLATS woody extent product according to forest definitions, this study provides a nuanced breakdown of annual clearing statistics based on structural criteria.

Methods / Results:
This study first explored the relationship between the SLATS woody extent product and top-of-canopy GEDI height retrievals by analysing over 26 million level 2B GEDI footprints for the year 2022. The area under the receiver operator characteristic curve was calculated using a binary classification of footprints within SLATS-defined woody areas to evaluate the spatial distribution of performance. Results overall show strong agreement between GEDI height retrievals and the SLATS woody extent across Queensland (mean AUC = 0.85). Tall and dense regional ecosystems such as wet eucalypt (mean AUC = 0.909) and rainforest (mean AUC = 0.889) performed the best, whereas low and sparse vegetation such as woodlands within hummock grasslands (mean AUC = 0.782) and eucalypt low open woodlands (mean AUC = 0.771) did not perform as well but demonstrated acceptable performance. GEDI height data were then calibrated and validated using extensive airborne laser scanner (ALS) mosaics spanning from 1999-2023 at 10cm, 50cm and 100cm resolution and a generalised additive model (GAM) was used to fit the data. All GEDI data for 2022 were then calibrated and intersected with Foliage Projective Cover (FPC) data. The probability that a given a point within the SLATS woody extent will meet a given definition of forest height (m) and crown cover (CC). Three international definitions of “forest height” were considered: the Food and Agriculture Organisation of the United Nations (FAO) (>=5m, >=10% CC); the National Greenhouse Gas Inventories (NGGI) (>=2m, >=20% CC); and the United Nations Framework Convention on Climate Change (UNFCCC) (>=2-5m, >=10-30% CC). Findings showed 60% of cleared vegetation met FAO, 65% met NGGI, and between 29% (high range) and 94% (low range) met UNFCCC definitions of forest. Results therefore show that a large proportion of the SLATS woody extent product has significant height and crown cover based on the proportion of the extent meeting NGGI, FAO and UNFCCC definitions. Furthermore, the majority of clearing involved the removal of vegetation with lower height and density.

Conclusion:
This study highlights that GEDI data can be used successfully to infer forest characteristics within the SLATS woody extent product, as well as provide insights into forest clearing - which is essential for informing land management strategies aimed at biodiversity and carbon storage. Future work is aimed at exploring future SLATS report data and comparing results with other state-level SLATS programs such as those undertaken by the New South Wales state government. Finally, investigation into a more comprehensive and spatially-dense dataset by incorporating ICESat-GLAS data or the proposed Earth Dynamics Geodetic Explorer (EDGE) should be explored.

Estimation of tree cover extent using ICESat-2 spaceborne lidar data

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Introduction/Aim:

The boreal forest biome is experiencing a northward shift and structural changes due to climate change. Spaceborne lidar systems are suitable for estimating these changes in the biome as they have global coverage and high temporal resolution, while simultaneously providing information on the vertical structure of the canopy. In this research, our objective was to estimate the boreal tree cover extent using ICESat-2 spaceborne lidar data. The Food and Agriculture Organization of the United Nations (FAO) defines forest, among other criteria, based on the area's land use class. Since land use is not determinable solely via remote sensing, tree cover extent is estimated instead of forest area. An area with tree cover is defined in this study as an area having canopy cover of at least 10% and dominant height of at least 5 meters.

Methods:

The study was conducted in two study areas in Finland: Pello and Valtimo. The main tree species were Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and birches (*Betula spp.*). This study utilized field plots with canopy cover and dominant height measurements, wall-to-wall airborne laser scanning (ALS) data, and ICESat-2 data (ATL03 and ATL08 products). The field plots and ALS data were used to build models for predicting canopy cover and dominant height on the ICESat-2 locations. These attributes were then used with ICESat-2 derived height metrics to train tree cover classifiers for ICESat-2 data.

The tree cover was predicted with two methods: logistic regression and prediction-based classification. In logistic regression, the area was classified as having tree cover if the class probability was 50% or over. In prediction-based classification, the canopy cover and dominant height were predicted first. If the predicted canopy cover was over 10% and the predicted dominant height was over 5 m, the area was classified as having tree cover. The constructed models were cross-validated by applying models constructed in Pello in Valtimo and vice versa.

Results:

This study yielded promising results with tree cover prediction accuracies varying between 89.8–95.6% (validation 88.1–95.8%) with logistic regression and between 89.5–95.4% (validation 89.6–95.4%) with prediction-based classification. The F_1-scores of logistic regression and prediction-based classification were between 0.93–0.97 (validation 0.92–0.98) and 0.93–0.97 (validation 0.93–0.97), respectively. The canopy cover models had relative root mean square error (rRMSE) values ranging between 29.5–60.1%, and the dominant height models had rRMSE values between 19.1–41.0%. The performance of the models was highly dependent on the quality of the ICESat-2 data. The accuracy was consistently lower in Pello compared to Valtimo, where the ICESat-2 data was of better quality with less noise. In future research, improved noise filtering methods should be applied to decrease the effect of background noise.

Global Forest Watch - a decade of monitoring global forest extent and change

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Global Forest Watch (GFW) represents a unique research to operations global forest loss monitoring capability. Operational monitoring of forest loss is increasingly important as it impacts a variety of key ecosystem services, for example biodiversity loss due to reduced habitat, global warming due to deforestation, and impairment of hydrological systems due to land use expansion. This talk will recount the history, current state, and future plans for the global forest product suite. The approach has changed over time, due to improved data inputs, methods, and other refinements. Forest loss nominally constitutes tree cover mortality for trees >=5m and >=30% tree cover extent, and includes natural and human-induced loss events. Attributing loss dynamics to causes/drivers is an ongoing objective, and now includes a concurrent loss due to fire layer. Drivers of forest loss are otherwise attributed through sample-based analyses. Forest extent reference maps allow specific geographies to be studied, for example trends in the rate of primary humid tropical forest loss. These high carbon stock, high conservation value forests are the focus of global climate change mitigation strategies, and GFW capture their relative loss at national scales. Future versions of the product will include a consistent algorithmic framework informed by forest structure, building on prototype work estimating woody canopy cover and tree height. Harmonizing forest loss, gain/recovery, and structure will mark a major advance in consistently tracking both state and dynamics of the globe's forests. Forest alerts have been expanded globally and reflect a near-real time source of forest disturbance information for land managers. Global forest loss maps also facilitate IPCC-compliant forest extent and loss area estimation from probability-based samples. Integral to any forest mapping and monitoring program, probability-based samples of reference data allow for unbiased estimators with known uncertainties to be applied. Key to these reporting methods is leveraging accurate maps such as the GFW forest loss layer, which acts as a targeting mechanism in generating precise and unbiased area estimates. GFW is a first of its kind global monitoring system, advancing in capability as data and methods allow in order to generate the most timely and accurate information available on the state of the world's forests.

The Concurrent Artificially-intelligent Spectrometry and Adaptive Lidar System (CASALS):

A New Capability for Monitoring Forest Structure and Function from Space

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The CASALS team at NASA's Goddard Space Flight Center and its partners are developing new lidar technologies and measurement methods that will significantly advance spaceflight lidar remote sensing capabilities. These advances will serve four of the observing challenges put forward in the United States National Academy of Sciences 2017 Earth Science Decadal Survey. CASALS will be able to conduct the first lidar swath mapping of topography, forest structure and snow depth from space, providing crucial information for a wide range of studies such as those of forest productivity, habitat quality, snow-melt water availability and the impact of natural hazards. The swath mapping along with concurrent narrow-band multispectral imaging will enable deeper understanding, modeling and prediction of complex forest processes, such as how the 3D interception of sunlight by varied foliage types affects function and productivity. An airborne CASALS is being developed to demonstrate the technologies and capabilities, in preparation for spaceflight mission opportunities later this decade. Lidar components that are, or can be, space qualified are used along with commercial hyperspectral imagers. Airborne CASALS is scheduled for flights in August 2024 at an altitude of 8.5m. Flights will target NEON eddy covariance flux tower sites in the United States mid-Atlantic region. NEON conducts growing season 1m resolution airborne laser swath mapping and hyperspectral imaging at each flux tower site which will serve as validation for the CASALS data.

The CASALS swath mapping is accomplished using a first-of-its kind, non-mechanical, beam scanning method and dramatic advances in lidar measurement efficiency. The transmitter combines a wavelength-tuning seed laser, centered at 1040nm, pulse carving electronics producing 2ns FWHM pulses, a high peak-power fiber amplifier and transmission through a wavelength-to-angle diffraction grating. From a 500km orbit, the transmitter can create 1,200 laser footprints scanned cross-track over an angular range of 0.825deg, corresponding to a 7.2km swath. Any subset of the 1,200 footprints can be adaptively selected by rapidly tuning to specific wavelengths. The receiver also uses breakthrough technologies, combining a grating spectrometer for solar background filtering, a linear-mode, single-photon sensitive, HgCdTe APD detector array to image the footprints, and time-multiplexed analog-to-digital waveform digitizing. In our near-term mission concept, deploying CASALS in low Earth orbit on a SmallSat, our performance modeling predicts we can operate the laser at 140Khz to map three 130m wide swaths, distributed across 7km, with overlapping 10m footprints spaced apart by 6m cross track and 3m along track. The expected density of detected photons for green foliage is ~1/m^2, which is ~10x greater than along ICESat-2 profiles, while using a 2x smaller receiver telescope so a lower cost SmallSat can be used. That density is sufficient to produce waveforms with signal-to-noise ratio similar to those of GEDI for 20m x 20m areas. In the near-term, the swath width is limited by the size of the detector array qualified for spaceflight use. In the longer term, we are working with our detector partner to have a larger array that could image footprints everywhere across the 7km wide scan width.

187

Monitoring the role of forests in the global carbon cycle with Global Forest Watch

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The Intergovernmental Panel on Climate Change's (IPCC) latest assessment report reminds us that forests play a crucial role in the global carbon cycle and in mitigating climate change. To act on that report and manage and protect forests – from policies to on-the-ground action – governments, companies, Indigenous Peoples and civil society need information on where forests are gaining or losing carbon.

To support these groups and others, Global Forest Watch (GFW) released global maps and associated annual statistics of forest carbon emissions, sequestration (forest carbon removals) and net greenhouse gas flux from 2001 onwards. These results were generated from a novel geospatial monitoring framework built to be improved over time as new and relevant information is collected by the broader research community, both on the ground and from Earth observation data.

This presentation will outline the rationale for designing such a forest carbon monitoring framework and will focus mainly on improved results achieved through various updates, enhancements, and comparisons with other studies made since the framework's original publication in 2021. These include but are not limited to updated maps of tree cover loss and gain and their attribution to different proximate causes, updated forest fire data with higher spatial resolution, a revised uncertainty analysis, and comparisons of GFW's results with national greenhouse gas inventories and other maps of satellite-based biomass change. Future research directions will also be identified, including improved spatial and temporal resolution of forest carbon removals. Case studies will highlight key actors and organizations that have used GFW's forest carbon data to help monitor, assess, and prioritize action to reduce emissions from deforestation, increase carbon sequestration from forest restoration and protect and enhance the global forest carbon sink.

Objective branch characterisation of forestry trials using PLS - the tool we've been waiting for?

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The characterisation of tree branch structure has undergone significant advancements since the introduction of digital methodologies and commercial terrestrial laser scanners (TLS) over the last two decades. The use of point clouds to study tree structure has matured to the point where multiple open-source and ready-to-use software tools are available for this purpose.

Point cloud-based branch characterisation has potential for enhancing tree breeding programmes, expediting the selection of superior genetics for forestry growing stock. Branching is a key trait that impacts on timber quality, however, current methods for assessing branching structure are often subjective and observational owing to the time-consuming and costly nature of objective alternatives. Advancements in remote sensing, particularly TLS, have facilitated objective assessment of branch structure, however, TLS often involves the use of expensive and heavy equipment which can be time consuming and prone to occlusion issues. In contrast, personal mobile laser scanning (PLS) is emerging as a system that offers a more cost-effective alternative that could reduce the impacts of occlusion through its enhanced mobility. The trade-off, however, is that PLS produces noisier point clouds due to lower-quality lasers that are incorporated within them.

This presentation will discuss recent trials utilising PLS for breeding selection, comparing its efficacy with manual measurements of branch structure (including branch diameter, branch angle, branch pattern and branch length), which were captured alongside scans from a PLS. Key metrics were derived from PLS point clouds and then compared with manual measurements to assess their accuracy. Data for the study was captured from two breeding trials of Pinus radiata: one at selection age (age 8), in which trees were access pruned to 2 m, and another at a younger age (age 5), which was unpruned. Sites were selected to evaluate the impact of tree maturity and access pruning on the PLS branch characterisation approach. The findings of this research offer valuable insights into the potential of PLS as a complementary tool for breeding selection programmes.

Modelling Annual Basal area increment of Scots Pine stands using Tree-ring Observations and Multisource Remote Sensing Data

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Accurate assessment of basal area increment (BAI) is fundamental to understanding forest growth dynamics. Annual BAI allows for the interpretation of growth trends and provides a direct measure of wood production. Most studies on BAI rely on data from permanent sample plots, where measurements are taken every few years. The other main source of data for BAI analysis is tree-ring data, but due to the high costs, tree cores are usually only available for a few trees per sample plot. Our study presents an integrated approach to modelling annual BAI utilising data from multiple sources, including an unprecedentedly comprehensive tree-ring dataset, airborne laser scanning (ALS) point clouds, Sentinel-2 and MODIS satellite imagery, and selected climatic variables derived from the TerraClimate dataset.

The study was carried out in Scots pine stands located in Poland. The 300 plots were distributed throughout the country with stratification in age and site condition classes. The tree-ring cores provided reference data for BAI, capturing growth patterns with annual temporal resolution. The field campaign was carried out in 2022. At each plot, the tree-ring cores were collected from all trees on the plot (minimum 30 trees per plot), giving more than 9,000 tree-ring core samples. Standard tree characteristics, including diameter at breast height and tree height were measured. The coordinates of the plot centres were collected with a high-precision GNNS receiver providing submeter accuracy. The BAI was calculated based on tree rings for the period 2017-2021.

The Generalised Additive Models (GAM) approach was used to model the relationships between tree-ring-derived annual BAI and the integrated suite of explanatory variables derived from remote sensing data, including: metrics derived from ALS point clouds (e.g. mean height of tree tops, stand density from tree tops, leaf area density), mean monthly values of number of vegetation indices (VIs) calculated from all available Sentinel-2 cloud-free imageries (e.g. NDVI, NDRE, NDWI, PPI), selected MODIS products (e.g. annual NPP, monthly PAR) and several climatic variables derived from TerraClimate dataset (e.g. precipitation, temperature, vapour pressure deficit). Thanks to using GAM approach, it was possible to develop complex model including interannual variability of VIs and climatic variables keeping the model interpretable.

The results obtained demonstrate the efficacy of the proposed approach in accurately predicting annual BAI. Remote sensing-derived variables substantially improved the accuracy of BAI compared to the model based solely on standard stand characteristics derived from traditional field measurements. The model developed based on data from 240 training plots including BAI observations from 2017-2020 and validated on observations from 2021 on 60 test plots, provided high accuracy: $R^2 = 0.78$, RMSE% = 30.1% and MAE% = 22.1%.

By combining the comprehensive tree-ring dataset with ALS and satellite observations, and using the interpretable GAM method, the performed study provides a thorough understanding of the BAI of Scots pine stands, providing valuable insights for applications of remote sensing data in forest monitoring and sustainable forest management.

Expanded observation of forest albedo documents significant offsets to reported carbon benefits

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Rapidly maturing frameworks for investing in and committing to mitigation of climate change through forest management have focused almost exclusively on the benefits of carbon sequestration and storage, without accounting for collateral changes in geophysical factors such as surface albedo. Newly available high-resolution albedo imagery from the Landsat 8 satellite, analyzed at 325,000 field plots monitored by the United States Forest Service, suggests that large areas of the country's forests have a net warming impact, and that albedo impacts offset approximately half of recognized non-soil carbon benefits, nationally. This research highlights a correctable source of uncertainty in operational monitoring of forest-climate interactions, and it may temper expectations for forest establishment as a means of mitigating global climate change.

Detecting drought stress using machine learning and hyperspectral drone imagery in a mixed Mediterranean forest

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Introduction/Aim:

Forests increasingly face drought, leading to trees' vulnerability to pests, diseases, and eventually death. Monitoring the water status of forest trees across large spatial scales is crucial for management and conservation. Leaf water potential (ψ_{leaf}) is a vital metric for characterizing tree drought stress and is thus used as an early warning signal. However, measuring ψ_{leaf} is time-consuming and, hence, limited to a relatively small area. Remote sensing enables rapid and non-invasive assessment of vegetation characteristics. Previous studies have shown the potential for using remote sensing spectral vegetation indices to assess ψ_{leaf} across vegetation types. Yet, this method was not tested in diverse, mixed-species forests at high spatial resolutions. Also, studies have yet to combine such data with machine learning (ML) to predict ψ_{leaf}.

We used high-resolution drone images to assess ψ_{leaf} in five key woody Mediterranean species. We developed ML models and compared them with traditional spectral indices. We also tested an ML classification model to determine whether it can distinguish between trees suffering from stress and those that do not.

Methods:

Six experimental plots (*c.* 0.05 ha each) were set in a mixed Mediterranean forest in central Israel (Yishi Forest). Rain shelters were placed beneath the canopies in three plots to reduce rain by *c.* 50%. Each plot had the five woody species that compose the mixed forest – *Pinus halepensis*, *Quercus calliprinos*, *Cupressus sempervirens*, *Ceratonia siliqua*, and *Pistacia lentiscus*. Five leaves from 3 individuals were sampled per each co-occurring woody species. ψ_{leaf} measurements were conducted between 9 am and 1 pm once every two weeks using a pressure chamber from October 2022 to March 2023. On the same day, hyperspectral images were taken at 60 m height using a Headwall Photonics nano-hyperspec camera onboard a DJI Matrice 600Pro drone. The background and shades were removed from the images using NDVI and NIR thresholds. ψ_{leaf} was correlated with 12 spectral indices, thousands of normalized difference spectral index (NDSI) combinations, and ML models fed with the hyperspectral data. We also applied an ML classification model to assess whether trees in the drought plots can be distinguished from those in the control.

Results:

ψ_{leaf} ranged between –1.0 MPa in unstressed trees and –5.0 MPa in rain-deprived *Cupressus sempervirens.* ML models showed only slight improvement compared to simple linear regressions of the commonly used spectral indices with ψ_{leaf}. The best model was derived from plot-level regressions with all species (R^2 = 0.8, RMSE = 0.31 MPa). The ML classification model using seven running averages over 40 bands had an accuracy of 88% and F1 of 0.88 in detecting trees suffering from drought stress (trees in reduced rainfall plots), even though physiological metrics showed little or no significant response.

Conclusion:

Our ψ_{leaf} ML model can be used with satellite data across sites since the best model was exerted on the plot level with all species combined. The ML classification model showed promising results in detecting early responses to drought, facilitating timely forest management practices like thinning or selected logging.

Temporal Dynamics and Forest Succession: National Annual Mapping of Tree Species in Canada using Landsat Time Series from 1984 to 2022

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Mapping tree species and changes in species distribution over time allows monitoring of successional processes and linking species distributions to regional, climatic, and disturbance processes. This knowledge is important for understanding the impacts of climate change and forest disturbance on tree species distributions and successional processes. Landsat satellites provide medium spatial resolution imagery suitable for mapping tree species over large areas and long periods of time. We used time-series Landsat imagery to produce annual maps of dominant tree species from 1984 to 2022 at 30-m spatial resolution for the 650 Mha of Canada's forested ecosystems. Landsat imagery and related spectral indices, geographic and climate data, and elevation derivatives are used as predictor variables trained with calibration samples from the Canadian National Forest Inventory (NFI) using a Random Forests machine learning algorithm. Based on prior knowledge of tree species distributions, classification models were implemented on a regional basis so that only those tree species expected in a given mapping region were modeled using local calibration samples. Modeling resulted in class membership probability values for each regionally relevant tree species for all treed pixels, as well as an attribution confidence indicator derived from the distance in feature space between the two leading classes. Preliminary annual results were informed by disturbance events to ensure the temporal consistency of tree species transitions in the time-series maps. The results of this study highlight the overall stability of tree species composition in Canada's forested ecosystems over the past nearly four decades, as well as the short-term dynamism of areas affected by disturbance events. The majority of Canada's forests were undisturbed during the study period, and therefore these areas may be composed of climax species or in advanced successional stages. Following stand-replacing disturbances, time is required for tree establishment and for young forests to transition to other species as part of successional processes. This temporal and spatial complexity underscores the importance of continuous monitoring of tree species. Annual wall-to-wall maps of tree species distribution from time series of remotely sensed data allow these trends to be mapped and represented, providing insight into the effects of environmental change on tree species composition, which is key to informing conservation and management policies.

Reliable Scalable Above Ground Carbon Estimates - Tracking Forests Globally

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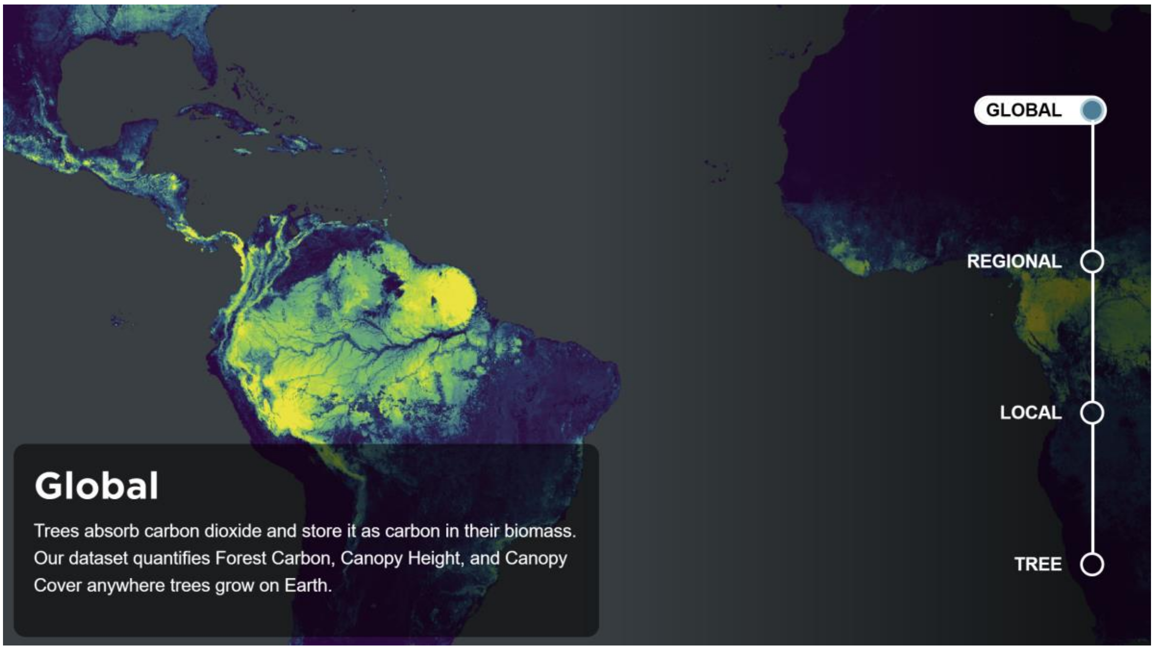
Introduction/Aim:
Forests play a critical role in absorbing vast quantities of carbon dioxide, but high-fidelity estimates of the carbon they store are costly and impractical at scale. PlanetLabs Forest Carbon data is designed to solve these challenges.

Methods:
PlanetLabs built a global dataset of aboveground forest carbon, tree height, and canopy cover estimates to make it easy to analyze every hectare of forest and woodland, anywhere on Earth. This is done using cutting edge machine learning models that fuse a rich archive of historical satellite observations with high quality, laser-derived reference data. Ideal for carbon project accounting, digital MRV, reforestation, and deforestation monitoring, Forest Carbon delivers estimates precise enough to monitor the complete spectrum of forest change, from million-acre wildfires to small agricultural clearcuts to single large tree selective harvests.

Results:
This has resulted in annual time steps in Planet Labs 10-year archive and, in the future, ongoing quarterly updates to track these dynamic ecosystems. Drawing on cutting-edge deep learning models and validated with high quality air- and spaceborne laser reference data, this captures more complete patterns of forest change over time with archive 30m data and, in the future, quarterly 3m Planet Monitoring data.

Conclusion:
This has been able to model Forest Carbon on a global scale. This means it’s straightforward to understand changes to the forests and woodlands you care about, no matter where they are. Track forests and forest carbon stocks across entire regions and within specific localities, all the way down to discrete parcels of land and even individual trees. Global coverage and tree-scale data removes the burden of needing to travel to remote locations and conduct field measurements or airborne surveys.



Valuing Forests using MLS, VR and ALS for Assessment of Recoverable Log Volume.

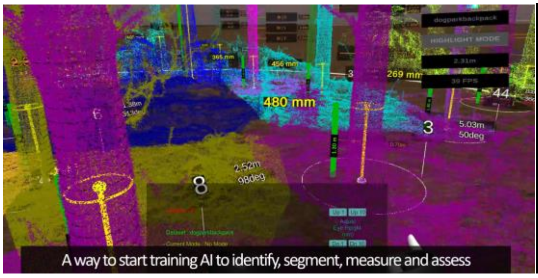
Mr David Herries[1]
[1]Interpine Group Ltd, Rotorua, New Zealand

Introduction/Aim:
A practical look over 1700 forest inventory plots collected and processed using mobile LiDAR scanning (MLS) for the forest valuation and merchantable volume yield table development. Covering a mixture of pine and eucalyptus forests the plots, the dataset is likely one of the world's largest ultra dense point cloud data collections for commercial (non-trial) forest yield, woodflow modelling, and subsequent forest valuation. The aim of the project was to replace manually measured forest inventory plots as part of the enhanced forest inventory (EFI) using airborne LiDAR (ALS), combined with single tree and area based yield imputations.

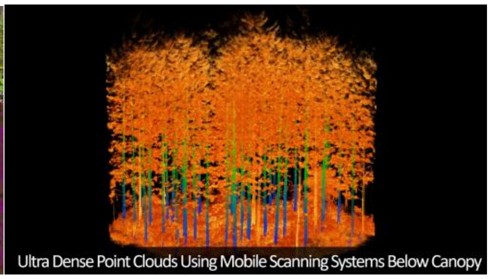
Methods:
Ground scanning using MLS LiDAR, in combination with 360-degree imagery, plot data was collected across approximately 1700 plots of both Eucalyptus and Pine. Plots were analysed in Interpine's TreeTools software using a combination of 3D point cloud machine learning (ML), with virtual reality (VR) full tree cruising. Converted into full cruise tree measurement, data was passed through YTGEN to provide forest yield tables. These provided input into a random forests model for forest yield imputation when linked with airborne LiDAR (ALS).

Results:
Active ML, by providing a feedback loop back from the auditing and labelling of 3D point cloud datasets using visualisation and VR, enhanced the ML. This significantly increased the productivity of data analysis and review in preparing the forest yield table development. Benefits include reduces field time, and resources. Enhancing ML for tree stem, branching and understorey detection. Tree positional data out provides for direct from tree canopy to base matching with airborne LiDAR datasets.

Conclusion:
Collection of ultra-high dense point clouds, labelling and through active ML training loop enhancing detection and automated assessment for forest plot data collection is a way forward for forest valuation and development of forest yields.



A way to start training AI to identify, segment, measure and assess


Ultra Dense Point Clouds Using Mobile Scanning Systems Below Canopy

Improving Land Use Classification Using Sentinel 2 and GEDI Data in the Andean Region

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Introduction/Aim:

The region from the Andes to the Amazon holds diverse ecosystems due to the different environments created by the great differences in elevation. These mountain ecosystems provide a variety of ecosystem services for human livelihoods. On the other hand, their functions have been severely degraded in recent years due to anthropogenic deforestation and forest degradation and large-scale fires caused by the El Niño phenomenon. Proper landscape management is necessary to conserve forests and maintain ecosystem services. For this purpose, highly accurate land use classification maps are necessary, and wide-area mapping using satellite data is expected. However, conventional optical sensors have limitations in understanding the state of forest degradation and classifying similar classes of reflectance spectra. Therefore, this study aims to improve the accuracy of land use classification by using 3D information from GEDI in addition to conventional optical sensors.

Methods:

The study area is located in southern Peru. A ground-truth survey was conducted in the field to obtain teacher data for classification. In non-forest land use, land use classes, geographic coordinates, and local conditions were recorded, and in forests, a survey was conducted to estimate forest biomass to provide one indicator of forest degradation.

Sentinel-2 and GEDI data were used as satellite data. Since the target area is susceptible to cloud cover throughout the year, we extracted cloud-free areas from all satellite data for one year within the target area in GEE. For the Sentinel data, the percentile data was used to plot height against percentile, and the pattern of this curve and the height at the 95th percentile were used to determine whether the area was forest or bush and to classify the degraded state of the forest.

Classification was performed on the cloud-removed Sentinel-2 satellite data using the ground-truth data and class data obtained from the GEDI data using the random forest method and compared to the results of classification without the class data obtained from the GEDI data.

Results:

In the study area, the "forest" and "shrub" classes are difficult to classify due to similar reflectance spectral characteristics. This may be due to the fact that "shrub" is not a forest, but has similar reflectance spectral characteristics to forest due to the large number of woody plants growing in it, and that many forests are also similar in texture with a height of 3 to 5 m, but only about 10 m. Using GEDI data, the differences between these classes The GEDI data could be used to clarify the differences between these classes. Isolated forests that are considered relatively degraded and surrounded by agricultural lands show a linear relationship of observed height to percentile of observed data, whereas inaccessible native forests show curves that suggest a large difference in height between the tops of trees and their surrounding canopy areas.

Classification accuracy using the random forest method with class data obtained from the ground-truth and GEDI data improved accuracy by about 5% compared to the results of classification without class data obtained from the GEDI data.

Evaluation of Disaster Prevention and Mitigation Functions of Mangrove Forests against Storm Surge by Remote Sensing

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Introduction/Aim:
Mangroves are distributed in the intertidal zone of tropical and subtropical coastal areas and serve as a buffer zone between marine and land areas. The recent rise in sea level caused by global climate change and the frequent occurrence of large typhoons have resulted in unprecedentedly large storm surges and storms, increasing the risk of disasters in coastal areas. This has led to great interest in the disaster prevention and mitigation functions of coastal areas, including mangrove ecosystems. Therefore, the purpose of this study is to evaluate the disaster prevention and mitigation functions of mangrove forests on a broad scale.

Methods:
The study site is a mangrove forest around Xuan Thuy National Park in Nam Dinh Province, Vietnam. This area, which covers more than 15,000 ha, has been reforested with mangroves by local residents under various projects.
WorldView-2 data, GEDI data, and drone data were used as remote sensing data.
In order to evaluate the disaster prevention and mitigation functions of mangrove forests over a wide area, information on the extent of mangrove forests is necessary to determine the width of the forest zone, and in addition, it is necessary to calculate the amount of mangroves as an obstacle to the direction of waves. Therefore, we used data from the WorldView-2 satellite to classify and extract areas of mangrove forests. Next, to calculate how much waves pass through the mangroves, we calculated the area of mangroves at 100 m width to the bank relative to the direction of the waves for various directions from the ocean to the land. Finally, height classification was performed using the mangrove height information from the drone data and GEDI data as teacher data and the texture of the WorldView-2 data. Using these results, the degree of disaster prevention/mitigation function of mangrove forests was evaluated by calculating how many mangroves are located within a 100-m width for each wave direction as obstacles that reduce waves.

Results:
Accuracy of mangrove classification was improved by masking the area around the mangroves to avoid misclassification. In the target area, the period of afforestation was limited to a relatively narrow period, so the values of forest canopy height obtained from the drone and GEDI were both concentrated at approximately 3 to 5 meters. Since a larger integrated value of mangroves in a 100 m width for various wave directions can be considered to have disaster prevention/mitigation functions, the integrated values were coloured to show the enhancement of mangrove forests and land, so that the relative disaster prevention/mitigation functions can be visually captured.

Conclusion:
The method presented in this study for broad-area evaluation of the disaster prevention and mitigation functions of mangrove forests is a method that takes practicality into consideration and allows for relative evaluation of functions. In contrast, by accumulating information on areas where tidal wave overtopping has occurred, this indicator will clarify which areas should be prioritized for countermeasures.

Combining remote sensing with biophysical process modelling to track carbon stocks and flows

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Forest biomass and its associated dynamics play an important role in the global carbon cycle and numerous other ecosystem services. In recent years, many researchers have attempted to map forest biomass across large areas using remote sensing modelling approaches. Typically, this involves training a machine learning (or AI) model with plot-based measures, allometric equations and remotely sensed covariates. Forest biomass maps are now frequently developed by companies for use in emissions estimation for carbon markets, supply chain analysis and compliance reporting.

Although often touted as the solution for forest carbon accounting, the stated accuracies of these maps are generally low – typically in the range of 60-70% for carbon stock, and likely lower for stock change. The differences between maps and methods are not often compared or well understood by those using them.

We compared several freely available maps of forest biomass and found large differences between products. This finding was not unexpected, given that remote sensors, particularly the current freely available optical and radar satellites, do not provide direct measurements of forest structure. In addition, the plot-based measurements used to calibrate and validate models often contain large uncertainties in themselves.

As well as the allometric-type maps often having large uncertainties, they only tell part of the story. Estimating the total emissions and removals from forests requires the tracking of carbon flows through all relevant carbon pools (e.g., the atmosphere, aboveground, belowground, dead organic matter, soil, harvested wood products, etc.). Biophysical process models offer a means to track carbon flows through the various pools over time and space. By combining remote sensing products with these process models, a more holistic representation of forest carbon dynamics can be established. Another advantage of process modelling is the ability to run models forward in time to create abatement potential scenarios.

Here, we used the Full Lands INtegration Tool (FLINT) to model forest carbon in eucalypt forests in NSW, Australia. We ran the model with different configurations, using different remote sensing based products to define forest types and trigger disturbance and recovery processes. The results suggest that the accuracy of these data inputs can have a large impact on model outputs.

In conclusion, we propose that process models, in conjunction with remote sensing products, offer an effective means to track forest carbon flows over time. However, accuracy is contingent on having access to reliable data inputs. Given the global importance of carbon accounting, more attention should be given to improving the accuracy of the input datasets needed to drive modelling processes, along with the consideration of all carbon stocks and flows.

Early prediction of regional red needle cast outbreaks using climatic data trends and satellite-derived observations

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[1]Scion, Christchurch, New Zealand, [2]Scion, Rotorua, New Zealand, [3]Flinders University, Adelaide, Australia, [4]Indufor Asia Pacific, Auckland, New Zealand

Introduction/Aim:
The fungal disease *Phytophthora pluvialis*, or Red Needle Cast (RNC), has become widespread within radiata pine, the dominant plantation forest species in New Zealand, particularly on the East Coast of the North Island.

Methods:
The impact of the disease was apparent from a visual assessment of Sentinel-2 imagery, a time series of which was then reviewed using a range of common spectral indices used as indicators of vegetation condition using Google Earth Engine (GEE). Assessment showed that a normalized index of the red and green bands were most sensitive to the discolouration caused in the upper canopy by disease expression. Using an image difference approach within an existing forest boundary dataset updated with harvest masking and dates informed by the time series assessment, the relative severity of the disease expression was calculated as a function of the difference between T1 and T2 red/green index values, using March as a pre-expression baseline, and September as the peak of expression. This process was completed over 5 years, from 2019 to 2023, and used to generate a plot database of disease expression within the East Coast region. The expression value was classified into no expression, low, medium and high classes and related to VCSN climatic data, with variables describing solar radiation, relative humidity, rainfall, wind, and temperature extremes.

Results:
Reviewing the Sentinel-2 classifications against RNC area manually digitized from concurrent very high resolution (VHR) satellite data, a good correlation is apparent. A random forest model was trained from the classified plots with climatic data sampled in GEE which was able to predict likely incidence of RNC with a high degree of accuracy across the 5 years of the study, with both years with little disease expression and years with a high degree of expression classified well. The four climate variables that offered the best relationship with the red-green index difference values were relative humidity, rainfall, radiation and maximum temperature, occurring in February, offering a 7-8 month advance warning before peak expression.

Conclusion:
Large-scale detection of RNC data using a simple image differencing approach is an effective approach to classify apparent disease extent and severity. A strong relationship between disease expression and climatic variables was apparent and offers a potential avenue for better future management of the disease by providing advance notice of possible disease hotspots for treatment before peak disease expression.

53

An engagement framework for phenotyping native trees in Aotearoa New Zealand, for Māori cultural purposes

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The use of remote sensing technologies for high-throughput characterisation of tree traits will unlock phenotyping opportunities in New Zealand forestry. Could these methods also be applied to benefit the distinctive values that Māori people place on their forests? A key research challenge here is to address the lack of universal understanding of how Māori select and value native trees for cultural purposes. Further to this though, we need an appropriate method to combine local knowledge, different expertise, and cultural views with often disconnected trends in digital innovation and socioeconomic development.

To this purpose the Rōpū Mahi framework (RMF) was conceptualised. Two years ago, this framework was operationalised via the Rōpū Mahi (RM), a working group that is made up of members of Māori forestry leaders, including Māori practitioners and Māori scientists, from a range of regions across New Zealand. A key task of the members has been to maintain a level of knowledge within a New Zealand government funded research programme entitled ‘Transforming Tree Phenotyping’ that spans species, scales, and leading technology applications set within paradigm contexts of genetic gains, climate change and Māori culture. Having a dynamic term of reference established inside the programme objectives and with a focus on the priorities of the members, as well as underlying mechanisms such as clear ways to value Māori knowledge, have been useful. Early indications are that this model of engaging with Māori is effective for introducing techno-cultural innovation in managing their forests. The next steps are to dive into the uses of leading-edge technologies to codesign methods and tools that can perceive tree characteristics that are important for their distinctive purposes, and to identify pathways that will enable Māori to leverage this knowledge.

Nexus of Certain Model-Based Estimators in Remote Sensing Forest Inventory

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Remote sensing (RS) facilitates forest inventory across a wide range of variables required by the UNFCCC as well as by other agreements and processes. The Conventional model-based (CMB) estimator supports wall-to-wall RS data, while Hybrid estimators support surveys where RS data are available as a sample. However, the connection between these two types of monitoring procedures has been unclear, hindering the reconciliation of wall-to-wall and non-wall-to-wall use of RS data in practical applications and thus potentially impeding cost-efficient deployment of high-end sensing instruments for large area monitoring. Consequently, our objectives are to (1) shed further light on the connections between different types of Hybrid estimators, and between CMB and Hybrid estimators, through mathematical analyses and Monte Carlo simulations; and (2) compare the effects and explore the tradeoffs related to the RS sampling design, coverage rate, and cluster size on estimation precision. Primary findings are threefold: (1) the CMB estimator represents a special case of Hybrid estimators, signifying that wall-to-wall RS data is a particular instance of sample-based RS data; (2) the precision of estimators in forest inventory can be greater for non-wall-to-wall RS data compared to wall-to-wall RS data; (3) otherwise cost-prohibitive sensing, such as LiDAR and UAV, can support large scale monitoring through collecting RS data as a sample. These conclusions may reconcile different perspectives regarding choice of RS instruments, data acquisition, and cost for continuous observations, particularly in the context of surveys aiming at providing data for mitigating climate change.

Large-scale Retrieval of LAI based on Spaceborne LiDAR ICESat-2

Dr Da Guo[1], **Dr Ronghai Hu**[1]
[1]University Of Chinese Academy Of Sciences, Beijing, China

Introduction/Aim:

Spaceborne LiDAR (Light Detection and Ranging), due to its superior canopy penetration ability and the capability to acquire three-dimensional canopy structure information, provides an important data source for the inversion of large-scale forest Leaf Area Index (LAI). The clumping effect is a significant factor affecting the accurate inversion of forest LAI by spaceborne LiDAR, and to date, no studies have fully utilized the three-dimensional structural information provided by spaceborne LiDAR to correct the clumping effect on a large scale.

Methods:

Therefore, this study focused on large-scale clumping effect correction and LAI inversion across forest areas in China based on the spaceborne LiDAR ICESat-2 and a point cloud segmentation path length distribution method.

Results:

The results show that the ICESat-2 LAI is in good agreement with the ground-observed LAI, indicating that the clumping effect has been corrected to a certain extent. Furthermore, comparing ICESat-2 LAI with MODIS LAI and GLASS LAI, it was found that ICESat-2 can capture higher LAI values (LAI > 6.0), while the MODIS and GLASS LAI products saturate near an LAI of 6.0, indicating that ICESat-2 LAI mitigates saturation issues.

Conclusion:

The point cloud segmentation path length distribution method is feasible in correcting the clumping effect and inverting forest LAI in China. This study may provide useful insights for future research on the global inversion of forest LAI based on spaceborne LiDAR ICESat-2.

Comparing aboveground biomass density maps derived from airborne lidar, satellite lidar, radar, and multispectral data across forested lands in Oregon, USA

Dr Andrew Hudak[1], Jennifer Bakken[2], Andrew Lister[3], Ty Wilson[4], Karin Riley[5], John Shaw[2], Roy Mita[6], Sean Healey[2], Francisco Mauro[7], Patrick Fekety[8], Matthew Gregory[9], Robert Kennedy[9], Chad Babcock[10], Neha Hunka[11], Laura Duncanson[11], George Hurtt[11], Carlos Silva[12], Sassan Saatchi[13]
[1]US Forest Service, Moscow, USA, [2]US Forest Service, Ogden, USA, [3]US Forest Service, York, USA, [4]US Forest Service, St. Paul, USA, [5]US Forest Service, Missoula, USA, [6]US Forest Service, Fort Collins, USA, [7]Universidad de Valladolid, Valladolid, Spain, [8]Colorado State University, Fort Collins, USA, [9]Oregon State University, Corvallis, USA, [10]University of Minnesota, St. Paul, USA, [11]University of Maryland, College Park, USA, [12]University of Florida, Gainesville, USA, [13]Jet Propulsion Laboratory, Pasadena, USA

Introduction/Aim:
Stakeholders need mapped aboveground biomass density (AGBD) estimates to inform forest management and planning decisions at multiple jurisdictional scales ranging from forest stands to landscapes, regions, and nations. Other needs are for accuracy, precision, repeatability, and transparency, such that the mapped AGBD estimates can be considered unbiased with respect to National Forest Inventory (NFI) plot data, to enable objective monitoring of forest carbon pools and fluxes to meet carbon monitoring, reporting and verification requirements in accordance with international agreements for greenhouse gas mitigation. Associated with these maps, stakeholders also need robust estimates of uncertainty to make informed decisions. An emerging challenge for stakeholders is choosing an AGBD map to use from among the number of AGBD maps increasingly available. Our objective was to compare the precision (RMSE) and accuracy (BIAS) of AGBD maps produced from different remote sensing datasets or using notably different methodologies.

Methods:
We compared ten AGBD products across the western US state of Oregon, which features a remarkable diversity of forest conditions across multiple jurisdictions. We subset global, national, or regional wall-to-wall AGBD products to the same, more limited spatial extent of AGBD map products derived from airborne laser scanning (ALS) data that are widely regarded as the best available remote sensing technology for mapping AGBD, with broad coverage available across most of the forested portions of Oregon. The AGBD map years ranged from 2000-2020, so we applied a 2009 forest/non-forest mask to all the AGBD maps considered, such that any AGBD estimates on potentially non-forest lands were excluded from consideration. We calculated the means of the remaining forest AGBD raster estimates, with resolutions ranging from 30m to 1000m, to 3 polygon scales of aggregation: counties of irregular shape and nominally large size, NFI sample hexagon tessellations of consistent, intermediate size (64,000 ha), and forest stand maps of irregular shape and small size. At the 2 larger polygon scales, NFI plot estimates could be summarized annually for ground-based validation. At the stand level, ground-based estimates for the same forest stands were obtained from the US Forest Service FSVeg database, which is collected largely ad hoc, i.e., not following a systematic sampling design like NFI plot data.

Results:
The ten AGBD maps considered were remarkably consistent for their precision; RMSE ranged from 56-68 Mg/ha, with lidar and multispectral image derived maps being more precise than those derived using radar. The BIAS statistic revealed more notable differences in accuracies, with the radar maps tending to underpredict AGBD by 12-35 Mg/ha and the AGBD maps derived using an ecosystem demography model tending to overpredict AGBD by 31-40 Mg/ha.

Conclusion:
Results confirmed the importance of calibrating the AGBD estimates using unbiased NFI data during mapmaking. The trends observed in the stand-level analysis were the same as trends observed at the county and NFI sample hexagon levels, confirming that ground estimates are useful for validation, even if they may be unsuitable for model calibration because they do not follow a robust sampling design and/or lack spatial precision and accuracy.

Intergovernmental Panel on Climate Change (IPCC) Tier 1 forest biomass estimates from Earth Observation

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Introduction/Aim: Aboveground dry woody Biomass Density (AGBD) maps produced with Earth Observation (EO) data have a large potential to periodically provide a transparent, consistent and replicable picture of the state of the world's forests. They can comply with the standards mandated by the UNFCCC, but are yet to formally adopted in international policy guidance. Our research provides the first compilation of AGBD estimates in the format of Intergovernmental Panel on Climate Change (IPCC) Tier 1 values for natural forests[1], sourced from NASA's GEDI and IceSAT-2 missions, and ESA's Climate Change Initiative (CCI). It also provides the underlying classification of global forests by ecozones, continents and status (primary, young (≤20 years) and old secondary (>20 years)).

Methods: Our approach is based on a Boolean compilation of various EO-derived datasets, which leverages the strengths of layers of satellite-derived forest tree cover, height, age and land use classifications. In summary, first, layers that identify a potential forest status/condition class (e.g. primary forests) are merged, and second, layers that identify sources of disagreement (e.g. presence of plantations or deforestation detected in the delineated primary forests) are used to remove areas of potential commission errors. The classification is run on the collaborative open-science could-computing system, the ESA-NASA Multi-mission analysis and algorithm platform (https://scimaap.net/). MAAP has capabilities to host relevant data, processing algorithms, and computing capabilities in a common cloud environment, linked to public GitLab/GitHub repositories, ensuring the transparency of our methods. Upon classification, mean estimates of AGBD (and their associated errors) are sourced from the GEDI's hybrid inference estimators[2], High northern latitude estimates from IceSAT-2[3] and the ESA CCI Biomass map of 2020[4].

Results: Across the world's natural forests (excluding planted forests), approximately 1678 Mha of primary forests, 1265 Mha of old secondary forests and 316 Mha of young secondary forests were identified. The trends in EO-derived AGBD estimates across these classes are captured well by the EO-datasets; like the IPCC values, the GEDI/ICESat-2 dataset estimates that primary Asian tropical rainforests and mountain systems harbour some of the highest AGBD globally, while the CCI dataset estimates that primary African rainforests harbour the highest AGBD. Model results show that there isn't sufficient evidence to indicate that GEDI/ICESat-2 estimates exhibit significant systematic differences to the IPCC values over all forest classes globally, although systematic differences are observed for the CCI estimates.

Conclusion: The results of this article are a pioneering international effort from CEOS, presenting AGBD maps in a format practical for policy and adoptable, upon review, in the IPCC Emissions Factors Database.

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National Forest Inventories and Earth Observation: Can a geostatistical approach fulfill countries' policy reporting needs?

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Abstract: Aboveground dry woody Biomass Density (AGBD) maps produced with Earth Observation (EO) data have a large potential to periodically provide a transparent, consistent and replicable picture of the state of the world's forests. Such map estimates may provide crucial support to nations and stakeholders reporting on forest carbon stocks, for example, to the United Nations Framework Convention on Climate Change (UNFCCC). Estimates can regularly contribute to complete and comparable aggregates for the Global Stocktake (GST) under the Paris Agreement. Yet, a recent synthesis of national-level reporting has concluded that only a handful of countries use EO-based AGBD maps in their (sub)national assessments of AGBD for policy reporting, highlighting a gap that is partially attributed to the lack of understanding on how to integrate forest plot-level data and the maps.

Under the Committee of Earth Observing Satellites (CEOS), a Biomass Harmonization activity has been initiated (NASA 2021), with a core objective of developing methods to integrate National Forest Inventories (NFIs) with EO-based forest AGBD or height maps. We present a geostatistical model-based (GMB) approach for the countries of Mexico and Mozambique, whereby their NFI data is modelled using the ESA Climate Change Initiative (CCI) Biomass maps and NASA GEDI forest height estimates. We further present methods that permit computational efficiency, namely through the Finite Elements approach, that discretises the domain and uses a pre-defined neighbour-based spatial model to estimate model parameters. Finally, we demonstrate how the results of the GMB can be used to (1) gap-fill locations with missing NFI plots, (2) estimate baseline AGBD in any arbitrary location. Both these demonstrations serve to fulfil the purpose of complete biomass stock inventories or estimation of emission factors that countries may use in combination with activity data (i.e. tree cover or forest loss) in policy reporting.

The approach is presented in an open-science framework on the ESA-NASA Joint Multi-Mission Algorithm and Analysis Platform (MAAP, https://scimaap.net/), which enables transparency, knowledge-transfer and flexibility to allow for the inclusion of new AGBD maps in the future. Finally, active support and liaising with the Global Forest Observations Initiative's Methods and Guidance Documentation component (GFOI 2020) will ensure that the approaches are communicated in manner aligned with country needs and policy requirements.

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Integrating UAV Lidar and Multispectral Data for Mapping Disturbance Severity in West African Relict Forests

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Introduction/Aim:
Forests are essential ecosystems that provide a wide range of services, such as carbon sequestration, habitat for biodiversity, and water regulation. However, they are increasingly threatened by human activities, leading to degradation and fragmentation. In West Africa, relict forests represent critical biodiversity hotspots but face significant anthropogenic pressures. Assessing their status and disturbance severity is crucial for guiding conservation and restoration efforts in these valuable ecosystems. This study aimed to explore the integration of unoccupied aerial vehicle (UAV) lidar and multispectral data to evaluate forest status and map disturbance severity across Ewe-Adakplame, a 560-ha relict forest in Benin, West Africa.

Methods:
We collected UAV lidar and multispectral data over the Ewe-Adakplame Forest using a fixed-wing UAV equipped with a lidar sensor and a multispectral camera. The lidar data was processed to generate a canopy height model (CHM), from which structural metrics describing canopy height, cover, gaps, and surface complexity were extracted. The multispectral data was processed to derive five key vegetation indices related to moisture availability, productivity, and foliar health: Green Normalized Difference Vegetation Index (GNDVI), Enhanced Vegetation Index (EVI), Soil Adjusted Vegetation Index (SAVI), Normalized Difference Red Edge (NDRE), and Leaf Chlorophyll Index (LCI). To develop an Integrated Disturbance Index (IDI), we first analyzed the correlations between the lidar-derived structural metrics and the multispectral vegetation indices. Significant positive correlations were observed between canopy height and spectral indices, such as NDRE (r=0.709) and LCI (r=0.693), indicating joint disturbance effects on forest structure and function. We then condensed the correlated height and spectral indices via Principal Components Analysis (PCA) to create the IDI, which was used for categorical mapping of low, medium, and high disturbance severities.

Results:
The IDI revealed that 25.8% of the Ewe-Adakplame Forest experienced low disturbance, while 45.7% and 29.5% of the forest underwent medium and high disturbance severities, respectively. Accuracy assessment using independent field measurements showed that the fused index (overall accuracy=88%) outperformed the individual datasets (lidar: 80%, multispectral: 78%) for disturbance detection. Integrating lidar and multispectral data provided a comprehensive understanding of forest status and disturbance severity, enabling more targeted conservation and restoration efforts.

Conclusion:
With three-quarters of the Ewe-Adakplame Forest undergoing medium to high disturbances, urgent interventions are imperative to strengthen resilience and prevent further declines. Protecting intact (low disturbance) zones through conservation enforcement and active restoration can help check further declines. The fusion method demonstrated in this study can be widely applied across West Africa to support effective conservation and restoration efforts. By integrating UAV lidar and multispectral data, we can better understand the complex interactions between forest structure and function, ultimately guiding more informed decision-making for forest management and conservation. This approach has the potential to significantly improve the assessment and monitoring of forest ecosystems, ensuring their long-term sustainability and the preservation of the vital services they provide.

165

Modelling the future growth of trees based on the airborne laser scanning based metrics

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Forests have a significant role in climate change mitigation as they act as carbon sinks and storages. More accurate estimates of forest growth and the climate effects of local forest operations are needed for carbon-neutral and climate-friendly forest management. Therefore, there is a need for new growth models that provide reliable decision support.

Growth is one often predicted tree variable and it has been examined in previous studies with growth models that have been developed both for tree- and stand level. Growth characteristics can be used either at the past forest growth monitoring or in the future forest growth prediction models. Typical predictors in growth models include tree diameter, site quality, competition index (e.g., the basal area of larger trees) and spatial competition indexes. A less studied alternative to using remotely sensed data in growth models is the prediction of future growth directly from the remotely sensed data. It is also possible to combine these data sources. In growth prediction, there is always a lot of uncertainty due to the limited amount of predictive information and high natural variation in forest growth.

In this study future growth prediction is considered. Our aim is to use the most recent remote sensing materials to predict 5-year tree growth directly from the current and past remote sensing data. In combination with biological knowledge and spatial description of forests, we develop a new-generation forest growth model for practical decision support. Our hypothesis is that new lidar derived predictors for growth that include e.g. past development and spatial neighbourhood of the modelled tree are better than the conventional predictors.

Our data includes 37 field measured plots including tree locations, species, heights and diameters. Field plots have been measured in 2009, 2014 and 2019. Airborne laser scanning data (ALS) is available from the study area from the first two years. For the modelling, individual tree detection from ALS data is conducted. Tree level predictor variables are calculated from tree-wise point clouds. ALS features at the beginning of the growth period, past development of ALS features before the actual growth prediction period and tree- and forest level features are used in the development of the new growth model.

We analysed the significance of different ALS based metrics as the explanatory variables for the incoming diameter increment. Our preliminary results showed that especially the development of the height means, the lowest and the highest height percentiles and the lowest and the highest intensity percentiles seemed to be significant. Metrics based on the first and only echoes seemed to be more significant than metrics based on the last and only echoes.

33

Unlocking the potential of consumer-grade UAV laser scanners for accurate assessment of plantation forests.

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Introduction/Aim:
The sustainable management of plantation forests requires precise inventory techniques to collect data for various purposes, including tree growth monitoring, timber value assessment, and silvicultural planning. Unmanned aerial vehicle laser scanning (ULS) offers a cost-effective method to accurately estimate forest structural attributes at both plot and individual tree levels, thereby facilitating the acquisition of inventory data for informed decision-making in forest management practices.

Methods:
In this study, we evaluated ULS data collected using a consumer-grade sensor for its capability to detect and segment individual trees, create digital terrain models (DTMs) and canopy height models (CHMs), and predict two crucial forest structural attributes, diameter at breast height (DBH) and stem volume, across varying point densities. We also tested the performance of two modelling methods for DBH predictions: Partial least squares (PLS) and random forest (RF). This assessment was conducted in a radiata pine (*Pinus radiata* D. Don) plantation located in the North Island of New Zealand. The study site, being at an assessment age (9-years old), proved to be an ideal candidate for testing the precision of tree measurements used for selections.

Results:
The accuracy assessment of individual tree segmentation consistently revealed F1 scores exceeding 0.96 across different point densities. However, CHMs derived from lower-density point clouds consistently exhibited overestimations compared to those from higher-density point clouds. We also observed a systematic bias in CHM estimations associated with varying point cloud densities. In contrast, DTMs obtained from decimated point clouds showed minimal variation to the DTM created from the highest density point cloud, with the differences ranging from 0.02 m to 0.11 m across different densities. Predictions of volume and DBH reveal that PLS consistently outperformed RF models in terms of accuracy across varying point densities. There was little difference in models that used metrics extracted from point clouds normalised using the high-density point cloud DTM and those extracted point clouds normalised using their native DTMs. Using data from the native DTMs, DBH estimation using PLS had the lowest RMSE of 1.62 cm and the highest R^2 of 0.76 at a density of 12,200 points/m^2, while stem volume estimation yielded the lowest RMSE of 0.04 m^3 and the highest R^2 of 0.79 at the same density. Both RMSE values remained relatively stable from 12,200 to 400 points/m^2, with a gradual decrease to 50 points/m^2 and for intervals thereafter and a more pronounced decline at densities below 10 points/m^2. Metrics that described the crown density and volume of the crown emerged as the strongest predictors of DBH across most point densities, while metrics describing the gap fraction and vertical canopy structure contributed minimally to models at all point densities.

Conclusion:
Overall, these findings hold significant implications, particularly for the precise estimation of DBH and stem volume at the individual tree level. They demonstrate the potential of cost-effective ULS sensors for rapid and frequent plantation forest assessment, thereby enhancing the application of ULS technology in plantation forest management.

The performance of TECIS for forest parameters estimation by combination of waveform LiDAR and multi-angle optical observations

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Introduction/Aim:

Accurately measurement of forest parameters is essential and challenging topic in forest remote sensing field. China's terrestrial ecosystem carbon monitoring satellite (TECIS) was successfully launched on August 4, 2022, becoming the world's first satellite for forest detection by integrating active and passive sensors. TECIS incorporates two key sensors, namely the Carbon Sinks and Aerosol LiDAR (CASAL) and the Directional Multi-Spectral Camera (DMC). CASAL consists of five large footprint lasers operating in the near-infrared band at 1064 nm. Each laser captures waveform data within a footprint diameter of approximately 25 m. DMC consists of five Visible and Near-Infrared (VNIR) cameras with specific observation angles at 0°, ±19°, and ±41° angles with a swath width of 20 km. TECIS is the first mission for forest carbon mapping by integrating full waveform LiDAR and multi-angle optical observations. Here we will evaluate its performances in typical forest types from Europe and China.

Methods:

The estimated forest height and biomass products using airborne LiDAR and field plots were used as references. Then the waveform from CASAL were used to estimate forest height and biomass at footprint level using random forest model. The BRDF reconstructed DMC reflectance was used to spatial extrapolation according to the CASAL footprint estimations. A deep neural network (DNN) was built based on the training datasets from CASAL and DMC. At last, full coverage forest height and biomass maps could be obtained from the multi-angle optical images**.**

Results:

The detailed performances of TECIS in typical forests from boreal(Switzerland/Europe), temperate (Genhe/China), subtropical (Puer/China), and tropical (Hainan/China) will be shown. The wall to wall forest biomass mapping accuracy is higher than 85% when validated at 500 m * 500 m scale, and 2.5 km * 2.5 km scale.

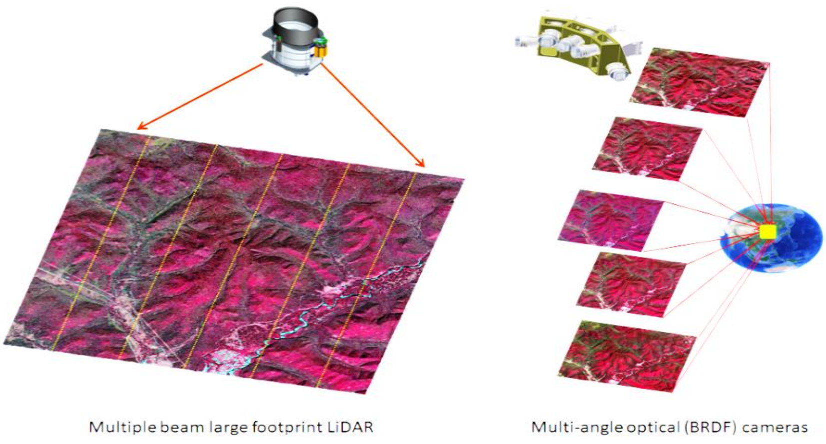

Fig.1 The full waveform LiDAR and multi-angle optical cameras configuration of TECIS

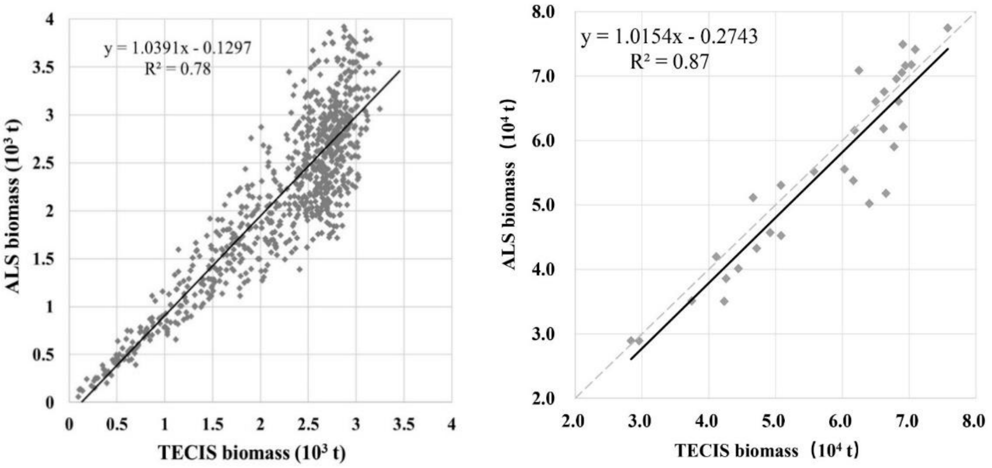

Fig. 2 Accuracy validation of biomass estimation at the (a) 500 m * 500 m and (b) 2.5 km * 2.5 km scale, respectively

Conclusion:

The TECIS satellite has achieved multi-beam (LiDAR) and multi-angle (optical) collaborative observation of forest parameters for the first time. Multi-beam full waveform LiDAR data provide forest parameter information at footprint level. Multi-angle information improves the wall-to-wall forest parameter estimation capacity.

The Impact of BRDF Correction on the Retrieval of Forest Leaf Area Index using Multi-Flightline Airborne Hyperspectral Imagery

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Introduction/Aim:
Airborne hyperspectral imagery provides detailed spatial and spectral insights, advantageous for retrieving forest biophysical and biochemical parameters. However, in practical forestry applications, large-scale multi-flightline airborne data is influence by Bidirectional Reflectance Distribution Function (BRDF) effects, limiting the accuracy of forest parameter models and introducing artifacts in forest parameter mapping.

Methods:
To evaluate the impact of BRDF correction on forest Leaf Area Index (LAI) retrieval and mapping, this study utilized hyperspectral imagery acquired by the Chinese Academy of Forestry's LiDAR, CCD, and Hyperspectral system (CAF-LiCHy) over the Mengjiagang Forest Farm (MFF, 193 km^2) in northeastern China, covering common coniferous species in northern China's temperate-boreal ecozones. A kernel-driven BRDF correction model was applied to multi-flightline airborne hyperspectral imagery for the large temperate forests. Subsequently, an investigation was conducted into the influence of BRDF correction on potential optimal wavelength ranges, Vegetation Indices (VIs), and six commonly used estimation models (i.e., PLSR, RFR, XGBoost, GPR, SVR, and ANN) associated with LAI modeling.

Results and Conclusion:
Our analysis yields the following key findings:

(1) BRDF correction notably enhances the accuracy of estimating large area forest LAI using multi-flightline airborne hyperspectral imagery, while also effectively mitigate artifacts in LAI mapping products. Specifically, after BRDF correction, the correlation with LAI showed a maximum improvement of $\Delta R^2 = 0.20$ in the visible and near-infrared (VNIR) bands, while employing VIs resulted in a maximum improvement of $\Delta R^2 = 0.32$. The estimation model exhibited a maximum increase of $R^2cv = 0.28$, and a maximum decrease of $\Delta RMSEcv = 0.25$.

(2) Through repeated experiments in two study areas, it was found that regardless of whether BRDF correction is applied to airborne hyperspectral data, within the VNIR range, the optimal wavelength ranges for reflectance most correlated with LAI are within the NIR bands (780-990 nm), while the weakest correlations are observed in the green (540-600 nm) and red (690-720 nm) bands. Additionally, it was found that due to the complexity of real forest scenes, the absolute contribution ranking of VIs to LAI retrieval remains unstable even after BRDF correction, but some NIRrelated VIs perform relatively well.

(3) Although the RFR exhibits the best performance in this study (MFF: $R^2cv = 0.77$, $RMSEcv = 0.55$), we still recommended to use multiple estimation models for a comprehensive comparison to estimate practical forest biophysical and biochemical parameters.

Application of Hybrid Forest Fire Modelling (FLAM-Net) in South Korea's Planted and Managed Forests

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Forest fires represent a growing global concern, particularly exacerbated by heat waves induced by climate change. In addition to the shifting climate conditions, the complex interaction of natural factors and human activities underscores the pressing need for advanced predictive models. While existing models offer either interpretability through process-based approaches or automatic feature identification via machine learning, they each have inherent strengths and limitations. This research aims to bridge these gaps by integrating human expertise, essential for understanding forest fire dynamics, into a machine learning framework. Introducing FLAM-Net, a neural network derived from the wildfire Climate Impacts and Adaptation Model (FLAM) developed by IIASA, this study combines the insights of FLAM's process-based approach with the capabilities of machine learning. Tailored specifically for South Korea, where 27% of its forest is planted and 61% is managed forest, novel algorithms within FLAM-Net decipher national-specific forest fire patterns. Additionally, employing U-Net-based deep neural networks (DN-FLAM) enables multi-scale applications, resulting in downscaled predictions. The adapted FLAM-Net and DN-FLAM models reveal spatial concentration of forest fires near metropolitan areas and the eastern coastal region, with temporal peaks occurring in spring. Evaluation of model performance yields high Pearson's r values of 0.943, 0.840, and 0.641 for temporal, spatial, and spatio-temporal dimensions, respectively. Projected scenarios based on Shared Socioeconomic Pathways (SSP) suggest an increasing trend in forest fires until 2050, followed by a decline attributed to rising precipitation. This study underscores the advantages of hybrid models like FLAM-Net and DN-FLAM, seamlessly integrating process-based insights with artificial intelligence for enhanced interpretability, accuracy, and optimization. The findings provide substantial scientific evidence for understanding forest fire dynamics, particularly in planted and managed forests that are also vulnerable to human disturbances.

***Keywords**: hybrid modeling, neural networks, forest fire, climate change*

UAV-LiDAR as a scaling tool for quantifying vegetation biomass and structural diversity in heterogeneous landscapes

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Quantifying the spatial diversity of above ground biomass across landscapes is essential for carbon accounting and habitat structural diversity assessment. As the need for natural ecosystem accounting increases globally, accurate maps of above-ground biomass are essential for fostering trust and transparency in natural capital markets. However, in the heterogeneous landscapes of Australia's rangelands—marked by low, variable rainfall and disturbances such as fires and droughts—this task poses significant challenges. High-resolution 3-D structural data collected by survey grade UAV-LiDAR offers a potential pathway for quantifying landscape heterogeneity and incorporating it when upscaling to larger area satellite-based observations.

We used field-based estimates of above ground biomass in conjunction with a high-quality UAV-LiDAR data (Riegl VUX-120 payload on Acecore NOA airframe), to capture spatial variability across diverse Australian rangeland landscapes and explored the potential for scaling biomass from plot (1 ha) to landscape scales (100-1000 ha). The field data was used to train and test Random Forest models based on structural metrics derived from the UAV-LiDAR surveys. Our analysis showed that UAV-LiDAR structural attributes were able to account for 75 % of the variability in above ground biomass, with an RMSE of 8.49 Mg ha $^{-1}$ across diverse landscapes.

Our findings show the potential for UAV-LiDAR to be used as an intermediate scaling tool to derive biomass estimations at landscape scales (100-1000 ha) from plot level (1ha) estimates, which are required for land managers and natural accounting programs. Furthermore, we illustrate how UAV-LiDAR can complement satellite-based models, and can be used to to establish scaling pathways, enhancing the spatial and temporal coverage of observations from landscapes to regional scales. Such large-scale monitoring tools will become increasingly important in addressing global challenges of natural resource accounting and habitat conservation.

Modeling Urban Trees with Mobile Lidar to Mitigate Urban Heat

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Introduction/Aim:
Urban trees are an easily overlooked component of the built environment, providing numerous benefits such as improved air and water quality, carbon sequestration, and providing shade, mitigating urban heat island effect. To better understand the importance of the various ecosystem services provided by urban trees, we must be able to map, identify, and measure individual trees as accurately and efficiently as possible.

The overall goal of this project is to map urban trees on a portion of a university campus and estimate their biophysical parameters, such as tree height, diameter at breast height, and crown diameter, using mobile lidar. The specific objectives will be to: develop the methodologies of mobile lidar data collection and analysis, compare direct and derived biophysical parameters against field-collected forest inventory data, and quantify the cooling effect of urban trees.

Methods:
Mobile lidar data were collected in the winter of 2023 using a GeoSLAM ZEB Horizon laser scanner mounted to a backpack while riding an electric scooter. GPS reference data were collected using a Trimble Geo7x concurrent to the lidar scan. The forest inventory was conducted in the spring of 2023. Within the scan area, n=120 trees were randomly selected and measured for diameter at breast height (DBH), total tree height (h), and identified by species. DBH measurements were collected using a steel diameter tape, and tree heights were collected using a TruPulse 200 laser rangefinder.

Results:
In a bivariate fit of field vs lidar-derived DBH measurements, we found an R2=0.868, RMSE=0.076, and $p<0.0001$; comparing field vs lidar-derived height measurements yielded an R2=0.957, RMSE=0.477, and $p<0.0001$. Cooling effect is still being investigated.

Conclusion:
From this work, we can develop localized allometric equations in an effort to scale-up our estimations to a larger geographic area with airborne laser scanning. Additionally, we can model tree shade output, quantifying cooling effect, mitigating urban heat. We can then identify areas of greatest concern, and coordinate with city planners to appropriately landscape with green spaces and water features, creating improved areas for recreation and urban wildlife.

Assessing forest regeneration status using UAV-based multispectral sensors.

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Forest regeneration monitoring focuses on assessing and tracking the process of natural or assisted regeneration of trees within a specific forest land area. Monitoring approaches typically involve field surveys to assess the tree seedling density, height, growth rates, and species composition. The forest stand regeneration monitoring is important for forest management in the future, providing insights into the effectiveness of regeneration techniques, and thus enabling more adaptive management strategies. Monitoring data are essential to improve the overall regeneration success under conditions of various disturbing factors. The utilization of Unmanned Aerial Vehicles (UAVs) for monitoring of young forest stand regeneration is gaining increasing focus as a cost-effective and efficient method. There are several benefits of using UAVs for forest regeneration monitoring, including rapid and frequent data acquisition, reduced labour-intensive field surveys. UAV-based monitoring provides a cost-effective alternative to traditional methods while maintaining data accuracy and reliability. In this study, we evaluate the potential of utilizing Unmanned Aerial System (UAS)-acquired very high spatial resolution imagery to provide structural information on pine forest regeneration in previously clear-cut stands in Lithuania. Around 200 clear-cut areas with 4-20 years old regeneration were imaged using rotor-wing type UAV. Using the acquired images (RGB and NIR), dense photogrammetric point clouds and orthophoto were produced for every clear-cut area. Each area was field sampled using conventional regeneration inventory approach. Several regeneration inventory approaches were tested both emulating conventional ground sampling and introducing new schemes, all utilizing information extracted from the images and point clouds. Several approaches were investigated to extract the information of regenerated pine seedlings, like object-based image analyses, deep learning and more simplistic image classifications based on spectral and structural information. Operational proposals on using UAV-based imaging and data processing for forest regeneration inventories were elaborated and evaluated for economic efficiency and implementation feasibility.

Increasing fire resistance in needleleaf forests through mixing with broadleaved trees

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Introduction/Aim:

Numerous factors can influence the frequency and intensity of forest fire. Among many, species composition is one of the key determinants of how forest fire can affect the damage of forest ecosystems and its recovery. This study evaluated the vulnerability of forest fire damage and forest fire resistance according to species composition of forest stands (i.e., proportions of needleleaf (NT) versus broadleaved trees (BT) within forest stands).

Methods:

After a forest fire event in South Korea, fire damage severity was assessed based on the comparison of the Normalized Burn Ratio before and after the event that was acquired from Sentinel-2 imagery. We further used 3 m of PlanetScope imagery to (1) quantify species composition between NT versus BT within 30 m of Sentinel-2 pixels and (2) analyze the degree of fire damage as well as recovery based on changes in the timing of phenological events and vegetation index.

Results:

The results show that the NT dominated forest stands suffered more damage from fire than the BT dominated stands, and the differences increased as the fire severity increased. In the NT dominated forest stands, increases in the proportion of BT led to decreases in fire damage, while there were no such correlations in the BT dominated forest stands. In addition, the NT dominated stands showed more delayed phenological events both at the start and end of growing seasons than those in the BT dominated stands, implying the slow recovery of forest stands after the fire in the NT dominated stands.

Conclusion:

Our results showed differences in the fire damage and recovery according to species composition and demonstrated that the higher fire resistance of BT could enhance the fire resistance of a forest stand. These findings suggest that considering tree species diversity is essential for restoring fire damage areas, especially in the context of climate change, where an increase in wildfire frequency is expected.

Small area composite estimators in a simulation test

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Decision makers need information for smaller areas than the National Forest Inventories can reliably provide. For instance, the Finnish National Forest Inventory produces municipality level results based on the K nearest neighbor method. These results are calculated from the field sample plots either by adjusting the sample weights with the K nearest neighbor weights, or by using post-stratification based on the predicted volume. The former approach provides a (potentially biased) indirect model-based estimate, the second an unbiased direct design-based estimate. Design-based approach is attractive, but not always feasible due to low numbers of field plots in small municipalities. Moreover, the indirect K nearest neighbor estimator is lacking an analytical estimator for the variance. A composite estimator combining the indirect model-based and direct design-based estimates could be a feasible solution. In this article, estimators for small-area estimation are analyzed in a simulation experiment with a varying size of the small areas and varying quality auxiliary data. The potential of composite estimators is assessed based on the true standard errors and RMSEs in the simulation experiment. The results show that direct estimators and composite estimators work reasonably well with varying quality models, but the performance of indirect estimators is highly dependent on the quality of a model. Linear models with limited weight for observations outside the area and K nearest neighbor model performed better than unweighted linear model. This suggests that the localization of the fixed parts of the models for the small areas is beneficial. EBLUP approach also performed well, both in connection of a K-NN model and a linear model. More research is needed to clarify how many and/or how far sample plots should be included from the outside of the domain, how the plots within and outside of the domain should be weighted, and how these choices are affected by the goodness of a model.

Structural Parameter Estimation in a Complex Mixed Conifer-Broadleaf Forest: Insights from UAV RGB Imagery through Structural, Textural, and Spectral Metrics

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Introduction/Aim:

Forest structure is the three-dimensional arrangement of its components, plays a crucial role in understanding forest ecological functions. Quantitative assessments of forest structure rely on forest structural parameters that capture various aspects of this arrangement. While estimating these parameters is relatively accurate in even-aged and simply structured forests, it remains challenging in complex mixed forests. Simply structured forests can often be accurately predicted with a smaller set of remote sensing metrics. However, the complexity of mixed forests demands a broader range of variables due to their dependence on multiple factors. In this study, we utilized UAV RGB imagery and an area-based approach to estimate several key structural parameters: Our objective was to identify suitable structural, textural, and spectral UAV metrics as explanatory variables for predicting forest structural parameters with high accuracy.

Methods:

We utilized the DJI Matrice 300 RTK UAV equipped with a Zenmuse P1 RGB sensor to capture imagery within mixed conifer-broadleaf forest compartments (com16 and com65-66) at the University of Tokyo Hokkaido Forest, Japan. Using structure from motion (SfM) technology and Pix4Dmapper photogrammetry software, dense point clouds were generated. Digital surface models (DSMs) and orthomosaics were derived from these point clouds, while canopy height models (CHMs) were created using DSMs and existing airborne LiDAR digital terrain models (DTMs). Structural and textural metrics were extracted from CHMs, and spectral metrics were derived from orthomosaics and these metrics were used to esimate dominant tree height (Hd), tree diameter at breast height (DBH), basal area (BA), stand volume (V), carbon stock (CST), stem density (Sden), and broadleaf ratio (BLr). We employed multiple linear regression (MLR) and random forest (RF) regression models, selecting UAV metrics through stepwise variable selection for MLR and ranking important UAV metrics by the percent increase in mean squared error for RF. Model accuracy was assessed via leave-one-out cross-validation against field data.

Results:

We found that a relatively high estimation accuracy was obtained for all forest structural parameters with the inclusion of structural, textural, and spectral metrics using both RF and MLR. Comparatively, the RF performed well to predict the field forest structural parameters. The models selected suitable UAV metrics as many as to predict the respective field forest structural parameters for obtaining high estimation accuracy. We obtained the estimation accuracy for Hd (R^2 = 0.86–0.93, RMSE = 0.61–1.02), DBH (R^2 = 0.45–0.89, RMSE = 0.96–2.24), BA (R^2 = 0.54–0.98, RMSE = 0.63–3.49), V (R^2 = 0.53–0.90, RMSE = 18.43–42.60), Sden (R^2 = 0.64–0.86, RMSE = 13.46–44.88) and BLr (R^2 = 0.54–0.87, RMSE = 0.03-0.56) using RF and MLR.

Conclusion:

The inclusion of textural and spectral metrics together with structural metrics was shown to be the best choice to predict the forest structural parameters in a complex forest, as its structure depends on many factors. The number of variables selected by the models differed depending on the field forest structural parameters. Comparatively, the performance of the RF model was excellent for all field forest structural parameters across the study area. Our reliable results will support foresters predicting forest structural parameters using UAV photogrammetry and thus contribute to sustainable forest management.

Leveraging Aerial RGB Imagery and Machine Learning for Monitoring Vegetation Encroachment in Dynamic Braided River Ecosystems of New Zealand

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Invasive weed species pose a significant threat to unique native ecosystems across New Zealand. Traditional ground-based monitoring is unable to address the widespread nature of this issue, being both time and resource-intensive. The coarse resolution of freely available satellite imagery limits its utility for detailed vegetation analysis, especially in complex and dynamic environments such as braided riverbeds, where vegetation encroachment is negatively impacting the ecosystem. This research harnesses the potential of high-resolution aerial imagery, utilizing visible Red-Green-Blue (RGB) bands to offer a novel and cost-effective solution for vegetation analysis.
The study employs RGB-based vegetation indices such as the Visible Atmospherically Resistant Index (VARI), Red-Green-Blue Vegetation Index (RGBVI), and Visible Vegetation Index (VVI). alongside a conversion from sRGB to linear RGB. This conversion is crucial for aligning the aerial image data with the raw reflectance values typically used in remote sensing, thereby significantly improving the reliability of vegetation analysis. The very high and statistically significant correlation between RGB-based indices and the well-established Normalized Difference Vegetation Index (NDVI) demonstrates the efficacy of RGB indices in reflecting vegetation dynamics, validating the potential of this approach for large-scale environmental monitoring.
Combining RGB-based vegetation indices with 3D canopy height models generated from overlapping image mosaics and applying machine learning algorithms, we present an integrated approach that significantly enhances the discrimination and monitoring of vegetation types. The methodology leveraged the conversion from standard RGB to linear RGB for improved accuracy in vegetation indices and employed support vector machine learning for refined classification, offering a comprehensive and nuanced understanding of vegetation encroachment patterns.
The methodology combined the simplicity and accessibility of RGB imagery with advanced analytical techniques, including the conversion from standard RGB (sRGB) to linear RGB to enhance the accuracy of vegetation indices. These indices, alongside machine learning classification and 3D canopy height models derived from aerial photogrammetry, provide a multi-dimensional view of vegetation structure and health. The incorporation of 3D rendering techniques to develop canopy height models adds a vital dimension to the analysis, enabling a detailed examination of vegetation structure and facilitating the differentiation of vegetation types. Machine learning algorithms, support vector machines, are harnessed to refine the discrimination of vegetation types, showcasing the potential of integrating aerial imagery with advanced computational techniques for vegetation analysis monitoring. The results underscore the efficacy of this approach in capturing detailed vegetation dynamics, thereby providing a scalable and efficient alternative to conventional methods and high-cost multispectral imaging.

Mapping forest type combining field plot and high-resolution data with machine learning in the boreal forest of Interior Alaska

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The boreal biome, the largest terrestrial biome on Earth, is increasingly vulnerable to climate change. This biome is warming twice as rapidly as the global average. Climate change has increased the temperature, frequency, severity, and extent of fires, which is resulting in forest type conversion and species ranges to shift. The increasing pace and scale of disturbances and rapid shifts in dominant forest type necessitate precise mapping to better understand ecosystem response to climate change and support effective management strategies.

While most previous vegetation mapping efforts have utilized coarse to moderate resolution satellite data, there has yet to be a spatially extensive and high-resolution forest type map. In this study, we present a framework to generate high-resolution forest type maps using a combination of field and aerial imagery in the Tanana unit of Interior Alaska. Our dataset is composed of high-resolution (1 m) canopy height, various vegetation indices derived from hyperspectral, and topographic variables including elevation, slope, aspect, and solar radiation collected by NASA Goddard's Lidar, Hyperspectral and Thermal Imager (G-LiHT) and field data collected by Forest Inventory and Analysis program (FIA).

We classified forest types at three different levels i) forest and nonforest, ii) hardwood, softwood, and nonforest, and iii) major forest types such as birch, black spruce, white spruce and nonforest. To achieve this objective, we applied and compared the performance of a convolutional neural network (CNN) with a XGBoost model. In this framework, we also studied the contribution of combinations of different data modalities to influence classifier accuracy in identifying forest types. We used SHapley Additive exPlanations (SHAP) method for understanding the importance of topographical factors that are related to forest distribution.

We found that the CNN model outperformed XGBoost model across all forest type classifications in terms of overall accuracy and macro average F1 score. The overall accuracy of CNN model was 93.06% for forest and nonforest, 82.59% for hardwood, softwood and nonforest, and 74.74% for birch, black spruce, white spruce and nonforest. In addition, we found canopy height and digital terrain model were the most important variables for all classifications. Further, we found several vegetation indices to promote detection including Anthocyanin Reflectance Index (ARI1) which was useful for differentiating between forest and nonforest. While vegetation indices such as Photochemical Reflectance Index (PRI), Pigment Specific Normalized Different (PSND), Gitelson and Merzlyak (GM1) and DATT2 were useful for differentiating between hardwood and softwood.

The CNN models were best for classification of boreal forest types. Additionally, we found that elevation was the most important topographical factor for driving forest type distribution. Further, we found that vegetation indices such as PRI, PSND, GM1 and DATT2 were more useful for differentiating between boreal forest types. We aim to use the high-resolution forest type map to produce wall to wall maps in the study area in future. The development of these kinds of frameworks are crucial for operationalizing remote sensing data in biodiversity and forest monitoring, which is especially important in large, remote areas such as boreal forests of interior Alaska.

Spatial approaches to modelling fire in New Zealand

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Introduction/Aim:
It is widely accepted that the New Zealand wildfire regime is predicted to become more severe with future climate change and increasing populations. "Smart firefighting" encompasses the collection and integration of data from a wide range of databases, sensor networks (including sensors on firefighters and equipment), computational tools and communication systems. Smart Firefighting ensures the flow of critical information when and where it is needed, and encompasses all four components of emergency management, namely reduction, readiness, response, and recovery. In the Fire and Atmospheric Science Team at Scion we are developing a tool to model the risk of fire across New Zealand to aid smart firefighting.

Methods and Results:
The Wildfire Intelligence Simulation Engine (WISE) and its predecessor Prometheus are wildfire growth simulation models developed in Canada which we have adapted for use in New Zealand. These models incorporate fuel, topography, and weather to provide spatially explicit fire behaviour and spread data for use with Geographic Information Systems. These models were chosen as they utilise the Canadian Fire Weather System, the Fire Weather Index and the Fire Behaviour Prediction systems which were already adapted and adopted as core systems for fire management in New Zealand. We included New Zealand specific fire behaviour and fuel models and validated the adapted model simulations against data from historic wildfires in New Zealand.

These models have been valuable for modelling fire growth during wildfire incidents and have been incredibly valuable for fire response. Scion previously developed tools using WISE, including a Fire Registry tool which uses hotspot detections from satellite data to model potential smoke hazard and fire growth over New Zealand. During conversations and collaboration with decision makers, we identified the need for a decision support tool integrating fire risk which could help with readiness and reduction.

Using WISE we are developing a tool to increase our understanding of wildfire risk across New Zealand which can then be integrated into a decision support tool to prioritise management actions. We are combining human-driven ignition probability and extreme weather conditions through thousands of WISE runs to build up information on the likelihood and severity of wildfires across New Zealand. Spatial ignition probability has been mapped using machine learning to determine the importance of different ignition drivers, such as population and distance to roads, and estimate a probability of ignitions based on proximity to these drivers. Weather conditions have been taken from weather stations across New Zealand during periods of extreme fire weather, and applied for any fires which occur within the same climatic spatial zone as the station. The resulting fire risk grid will show areas predicted to have the greatest fire risk under the 95th percentile fire weather conditions. Once spatial outputs are available, decision makers such as forest managers and owners will be able to consider fire risk in their planning and land management.

Monitoring And Extending Permanent Sample Plots By Remote Sensing Methods

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Introduction/Aim:
There are approximately 3000 permanent sample plots with seven main tree species in Hungary aiming growth and sylvicultural research. Most of the sample plots were established in the 60-ies. These very valuable datasets however have a quite significant drawback, as there is generally no single tree position recorded of the parcels. The primary aim of this research to demonstrate how state of the art remote sensing methods can effectively eliminate this drawback, and appreciably improve the general usage of the datasets.

Methods:
The stem mapping of some of these sample plots have been carried out by traditional filed surveys, terrestrial laser scanning, airborne digital photogrammetry and airborne laser scanning. The later ones were applied on UAVs. The methods were further developed to more effectively and more accurately detect the stem positions and DBH from terrestrial laser scanning dataset. New methods were introduce to detect the stem positions, height and DBH from very high resolution (1-2 cm) aerial images and airborne laser scanning.

Results:
A methodological guideline have been created to suggest an effective and accurate methods for stem mapping of these sample plots. Additionally the methods have been tested on six selected sample sites. The results can also be used to apply archive aerial photography to accurately estimate the height-growth of the sample sites.

Conclusion:
Applying our methods the usage of these sample sites can be extended in more accurate and advance research in Hungarian growth and sylviculture.

Acknowledgment:
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National mapping of forest biodiversity indicators based on NFI and lidar data

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Forests with high biodiversity value, such as primary and old-growth forests, play a vital role in carbon storage for climate mitigation and in providing suitable habitats for numerous endangered species. Consequently, various strategies and regulations under the EU Green Deal are aimed to map and strictly protect the remaining primary and old-growth forests. At present, national forest resource maps are operationally produced by integrating the National Forest Inventory (NFI) with national airborne lidar data on a large spatial scale. This approach provides spatially continuous maps of forest attributes, such as biomass and volume. However, these maps often limited in quantifying ecologically meaningful indicators related to primary or old-growth forests. In this study, we analyzed to what extent the NFI field measurements together with national airborne lidar and other data products, can be utilized to map forest age and structural complexity. We developed linear mixed effect and random forest models to predict forest age for different site indices, as well as single and multilayered forests across all forested areas in Norway, covering an area of 122,000 km². Our findings indicate that various ecological indicators can be predicted with overall accuracies ranging from fair (51%) to good (74%). Overall, the results demonstrate the potential of combining NFI and national lidar datasets to develop further ecologically relevant indicators for consistent biodiversity monitoring.

Forest Stand-Scale AGB Mapping over the farm Using Timber Cruising and Airborne LiDAR Data

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Introduction/Aim:
Airborne LiDAR data are one of the primary methods for large-scale forest biomass mapping. The commonly used area-based approach (ABA) typically relies on the statistical relationship between LiDAR point cloud feature parameters and plot-level forest biomass, with a spatial resolution usually between 20 to 30 meters (Tompalskia et al., 2019). Field data collection is a laborious task in biomass mapping using ABA predictive models developed from stratified inventory data from field plots (Du et al., 2023).

In plantations with logging plans, timber cruising is conducted to calculate the volume and biomass before and after harvesting for a certain number of forest stands. Forest stands, due to their homogeneous internal characteristics, hold potential as units for AGB estimation. Consequently, we propose a novel approach that utilizes timber cruising data as reference data and predictor variables derived from airborne laser scanner (ALS) data to establish a biomass estimation model at forest stand scale. Subsequently, this model is used in conjunction with automatically delineated sub-compartment ploygons to create AGB distribution maps at the forest farms scale.

Methods:
In this paper, we compile timber cruising data from 2017 to 2020 in the Mengjiagang Forest Farm(MFF),Heilongjiang Province, China, and align it with two sets of ALS data (2017 and 2020). Subsequently, we computed ALS-derived variables for each forest stand, including height, canopy density, and vertical structure variables. Across different forest types, we evaluated four variable selection and regression approaches: linear models based on Recursive Feature Elimination (RFE), linear models based on Stepwise regression (ST), linear models with ridge regularization (LMR), and Random Forest models (RF). Finally, by integrating the forest stands automatically delineated based on remote sensing data across the entire forest farm. (Xiong et al., 2024), we utilize the optimal model to conduct biomass mapping for the MFF.

Results:
The accuracy of the biomass estimation model at the sub-compartment scale is shown in Figure 1 to 2. For *Larix* and *Pinus sylvestris*, the optimal model, determined through 1000 iterations of tenfold cross-validation, achieved an average accuracy of R^2=0.87, rRMSE=0.16 for *Larix*, and R^2=0.76, rRMSE=0.14 for *Pinus sylvestris*. For *Picea*, due to fewer sample plots, leave-one-out cross-validation was used, resulting in an accuracy of R^2=0.98, rRMSE=0.12.

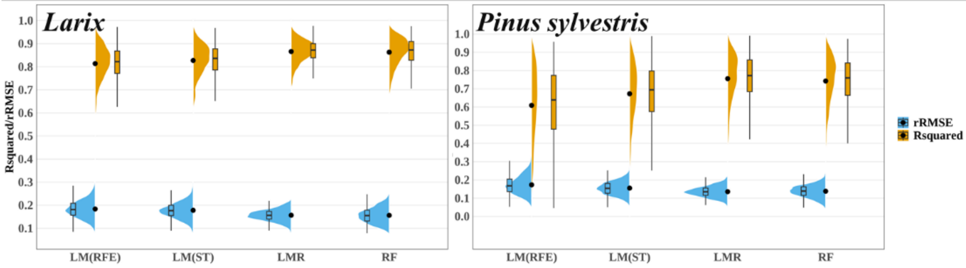

Figure 1: Precision of biomass estimation for *Larix* and *Pinus sylvestris* in forest stand.

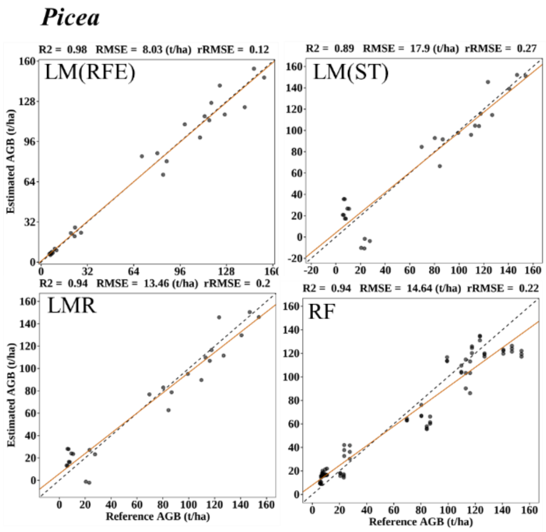

Figure 2: Precision of *Picea* biomass estimation in forest stand.

Conclusion:

This study validates the feasibility of forest Stand-Scale Biomass estimation using Timber Cruising and ALS Data, the accuracy is consistent with the widely used plot-scale ABA method. The dependency on actual measured sample plots is greatly reduced for mapping biomass at the farm level.

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Tompalski, Piotr., Joanne C. White., Nicholas C. Coops., et al. 2019. “Demonstrating the Transferability of Forest Inventory Attribute Models Derived Using Airborne Laser Scanning Data.” *Remote Sensing of Environment* 227 (6): 110-124. doi:10.1016/j.rse.2019.04.006.

Nationwide estimation of boreal forest above-ground biomass using ICESat-2 data

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Aim:

ICESat-2 (I2) remains as the only spaceborne lidar sensor that can collect forest resource information from the boreal zone above 52° N. Our objective was to train nationwide I2 models for estimation of above-ground biomass (AGB) and its uncertainty for the boreal forests of Finland. The estimates are validated regionally and against official statistics from the Finnish National Forest Inventory (NFI).

Materials and methods:

The nationwide I2 model was trained using data from six practical forest inventory projects implemented in 2021. The inventory projects were evenly spread throughout Finland, and each included its own field measurements (236-923 plots per site) and airborne laser scanning (ALS) data acquisition. A separate ALS proxy AGB model was trained for each project and applied to predict AGBs for 15 x 90 m I2 track segments that overlapped with the project area. The final I2 model was trained using a pooled data set of 9491 segments from the different projects. The I2 segments included both day and night observations but were required to have at least 100 classified photons and >60% high-quality photons. Segments with snow or cloud cover were removed.

The I2 model was applied to all forested I2 segments (n = 288391) obtained from Finland in 2021. The forest area was determined using a mask layer provided by the Finnish Forest Centre and covered a total of 267510 km^2. The nationwide total AGB and its uncertainty were estimated using a hybrid approach that only used the sample of overlapping I2 tracks, i.e. no wall-to-wall mapping was done. The uncertainty estimates included error contributions from the allometric tree biomass models, the regional proxy models, the nationwide I2 model, and the I2 track sampling.

Six additional inventory projects were used as test sites, where the segment-level predictions from the nationwide I2 model were validated against local ALS proxy models. In the nationwide level, the estimated biomass total was compared with an official NFI statistic obtained from field sampling.

Results and conclusion:

The nationwide I2 model for AGB had an RMSE = 45% in the pooled segment-level training data, and 37%–82% when it was validated at the six test sites. The total AGB estimated for Finland was 1229.7±144.5 million tons, while the reference value from NFI was 1308 million tons. Thus, the reference value was within the 95% confidence interval of our estimate. The slight underestimation may have been influenced by quality issues observed in ATL08 product, where canopy signal can sometimes be classified as noise. Nevertheless, our results show that ICESat-2 can provide reasonably accurate AGB estimates for large areas.

Productivity and Complexity – Linking two Fundamental Characteristics of Trees and Forests

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Introduction:
Several studies could already show that structural heterogeneity is positively related to stand level productivity. This relationship is assumed to be the result of complementary resource utilization or spatial niche-partitioning in canopies as a result of variations in species, age or dominance. Our knowledge of which structural traits of individual trees in a stand are related to the increased productivity of the stand community is however still limited. To date, increased canopy packing has been related to greater light interception, and greater light interception could be directly related to increased productivity. At the same time, increased canopy packing has also resulted in greater structural complexity, which has also been associated with greater productivity. Besides the optimal utilization of canopy space, complex growth might also favour productivity by increasing a tree's resource use efficiency. By creating a larger photosynthetically active area with the same or even less woody biomass, complex trees would exhibit a larger surface-area-to-volume ratio which could enable a higher benefit-to-cost ratio, since the constructing wood comes with maintenance costs. Within this study we want to further investigate why complex growth is beneficial for the productivity of trees and forests.

Study design:
The research training group EnriCo investigates the consequences of enriching European beech with native (Norway spruce) and non-native (Douglas fir) conifers in Central European forests. A quintet design comprising a set of three pure plots (European beech, Douglas-fir, Norway spruce) and two of the respective beech-conifer mixtures is established at eight locations throughout northern Germany. All of these 40 plots were scanned in 2021 using a mobile laser scanner (Geoslam ZEB-horizon). A subset of 20 plots were manually segmented, which provides around 1300 trees for further analysis on tree level. Besides most common tree characteristics, we will use the Box-Dimension (D_b) as one holistic parameter describing a tree's structural complexity. To get detailed information on the woody biomass of each individual tree, Quantitative Structure Models will be applied. As a proxy for productivity, we will use DBH measurements made in the field in 2017 and 2021 to derive basal area increment measures.

Expected results:
Deriving the crown surface area of each tree and its respective volume, we will test the surface-volume ratio of each tree against its D_b. This link was shown before but is the foundation for the intent of this project. Thereafter we will test the complexity of each tree against its productivity. The same will be done on plot level. Expected results are strong positive correlations between productivity and complexity, as these links were reported in the literature before. Since we know, how much each tree contributes to the plot complexity and productivity, we can further investigate the importance of individual complex growth to the overall productivity. Therefore, we expect a somewhat exponential relation as we hypothesize, that the most complex trees also contribute most to the overall plot productivity.

Modelling Foliar Moisture in Forests and Woodlands of Eastern Australian using Satellite Data and Radiative Transfer methods

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To understand water availability of potential animal habitat, we modelled foliar moisture of forests and woodlands in temperate and arid south-eastern Australia using remote sensing. We inverted the PROSPECT and GEOSAIL Radiative Transfer Models (RTM) using Sentinel-2 satellite reflectance data of 20m ground resolution to retrieve foliar moisture content (FMC). A published RTM Look-Up-Table was used in the inversion and filtered by ecological criteria from 24 sites sampled during one warm season, along a moisture availability and canopy cover gradient. The merit function used between simulated and satellite spectra was the spectral angle, minimised. We found predictions of forest and woodland FMC had a Root Mean Square Error (RMSE) of 19.9% dry matter content, this was an improvement of similar models using coarser resolution reflectance data, particularly so in explained variance with an r^2 = 0.62. Our analysis of predictions revealed some limitations of RTM parameters and of reflectance signals of sparse canopies. The results mean that we can accurately map foliar moisture at animal habitat scales, and that the estimates could be improved with a new forward stage of radiative-transfer modelling that includes ecosystem specific parameters.

ALOS-2 Robust Operational Deforestation Detection and Early Warning in Amazonia with JJ-FAST Ver. 4.2

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Monitoring of forest cover loss and tracking of related deforestation activities is one hot topic in Earth Observation today. Especially in the tropical rainforest belt, low-frequency L-band radar sensors have a unique potential to provide authorities with reliable information about ongoing deforestation all year round. This is mainly owed to their capability to “see” through clouds as well as through the entire forest canopy down to the very ground surface.

JICA and JAXA have been operating the JJ-FAST (JICA-JAXA forest early warning in the tropics) since mid-2016. The system exclusively uses ALOS-2/PALSAR-2 wide-swath ScanSAR images with 50-m resolution and a nominal revisit of 42-days. After relatively low reliability in the first years of operation, the performance has been drastically improving recently. In an unprecedented massive validation exercise over 3 1°x1°-sites in Brazil, the outstanding performance of the current JJ-FAST algorithm version 4.1, launched in November 2024, has been confirmed. The comprehensive validation dataset based on visual interpretation of Planet daily images allowed for the first time to assess both user's (UA) and producer's (PA) accuracies with high reliability. Since it is still not a trivial task to identify all deforestation cases in Planet data due to the often-limited image quality, such a validation data set is always associated with a certain degree of uncertainty. It is worth mentioning, however, that these uncertainties usually result in an underestimation of the JJ-FAST accuracy values. Thus, we assume that the validation results are indeed quite robust and meaningful. Using different parameter settings for optimized UA and optimized PA, UA for all detections larger 1.5 ha ranged between 70.2% and 40.7% and PA ranged from 28.2% to 38.7%, respectively. The reduced image quality of the ScanSAR mode makes it generally more difficult to achieve higher PA. The ratio between UA and PA is in the order of 3, i.e. for every point increase in PA we lose about 3 points in UA and vice versa. Based on this satisfying performance, the responsible authority in Brazil, IBAMA, has recently started to include JJ-FAST detections as core information for their operational procedures to combat illegal deforestation.

One main disadvantage of optical data-based validation and calibration approaches is the fact that useful optical image timeseries are only available during the dry season. That means the calibrated parameters may work well under similar environmental and meteorological conditions, but their suitability during the rainy season is largely unknown. To overcome this problem and to evaluate the Ver. 4.1 performance outside the dry season, we made great effort to validate every JJ-FAST detection in the Legal Amazon during the rainy season 2023/2024. Using this information on the true operational user's accuracy together with the seasonal statistics of the corresponding PALSAR-2 images, the seasonal parameters were adjusted to suit the more challenging wet conditions. At the time of writing the confirmed rainy season UA with the updated Ver. 4.2 parameter settings was 48.7% for all polygons sizes larger 1.5 ha and 78.9% for all polygons larger 10 ha, respectively.

Next-generation Radar Forest Monitoring with ALOS-4/PALSAR-3

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Forest monitoring is one prime objective for radar Earth Observation satellite missions. Especially in the tropical rainforest belt, low-frequency L-band radar sensors have a unique potential to provide reliable information in various applications including biomass estimation, deforestation detection, and forest classification. This is mainly owed to their capability to “see” through clouds as well as through the entire forest canopy down to the very ground surface.

Approaching the eagerly awaited launch in 2024, the ALOS-4 will be the 4th generation high-performance fully-polarimetric L-band SAR in orbit. Following its predecessor JERS-1, ALOS, and ALOS-2, ALOS-4 will be able to acquire dual and quad-pol wide-swath observations in high resolution Stripmap mode using cutting-edge digital beam forming technology. This will allow to overcome the limitations in operational forest monitoring with the current generation which can only provide frequent pantropical coverage in the coarse ScanSAR mode used, e.g., in the JJ-FAST system (JICA-JAXA forest early warning in the tropics). Together with the partial polarimetric NISAR mission which aims to achieve global coverage every 12-days and is also set for launch this year, the next-generation L-band Earth Observation era will provide new opportunities for systematic, seamless global forest observation from space.

Using a case-study over one of the ALOS-2 supersites in the Brazilian Amazon, we highlight the tremendous potential of frequent high resolution polarimetric L-band SAR observations to finally provide the means to stop illegal deforestation. Launched in May 2014 and nearing 10 years in orbit, ALOS-2 can arguably still be considered as the state-of-the-art SAR forest monitoring mission in operation. Over the Novo Progresso region, one of the severe deforestation hotspots in the state of Para, Brazil, ALOS-2 has acquired a unique dual-polarization timeseries in 10-m Stripmap mode. Between July 2019 and March 2024, 69 scenes were observed. Using JAXA’s next-generation deforestation detection algorithm, we demonstrate the tremendous potential of the upcoming 4th generation L-band satellite missions ALOS-4 to detect virtually all ongoing deforestation activities in the humid tropical forest. Thorough and comprehensive validation of the early warning polygons confirmed the highly reliable detection accuracy of well above 80% for both user’s and producer’s accuracies when considering all freshly deforested areas larger 0.5 ha. In addition, we will also address the potential of ALOS-4 quad-pol observations for various forest applications using different ALOS-2 examples.

Analysing sensitivity of Sentinel-1 SAR data to phenological and moisture dynamics in Central European Forests in a coupled modelling approach

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Changes in plant phenology, such as earlier leaf unfolding and delayed autumn senescence, can impact the water cycle resulting in limited availability of moisture during summer. In combination with higher temperatures, droughts increase forest fire danger in Central European forests. Due to the sensitivity of radar data to both, structural and dielectric properties of the scattering materials, microwave remote sensing offers potential to analyse phenology and vegetation water dynamics. Microwave data, e.g. Sentinel-1 SAR data, is widely used for retrieval of soil moisture, biophysical variables and more recently for live fuel moisture content (LFMC) in Mediterranean and Western US ecosystems. However, it is still unclear to which extent Sentinel-1 is sensitive to moisture content within temperate forests.
To address this, we couple a semi-empirical backscattering model (Water Cloud Model, Attema & Ulaby (1978)) with a dielectric mixing model (de Jong et al. (2002)) including in-situ measurements of LFMC and rainfall interception calculated from precipitation and throughfall based on the simple model by Rutter et al. (1971). In addition, information on soil moisture and vegetation structure (i.e. leaf area index, LAI) are incorporated into the model.
The model's calibration and inversion are tested at four sites in both evergreen needleleaf forest (ENF, spruce stand) and deciduous broadleaf forest (DBF, beech stand) using meteorological and ground data. Information on LAI and soil moisture allows applying the model spatially to a larger area. The calibrated model further allows to analyse individual effects of both vegetation descriptors, LAI and LFMC, by removing either structural or moisture related changes in the seasonal pattern of the Sentinel-1 signal. Understanding how these factors influence backscatter could improve accuracy and applicability of microwave remote sensing in assessing plant phenology and fire danger. Combining the advantages of a data and physical driven model enables the approach to being scaled to larger areas of similar vegetation even without the availability of in-situ measurements.

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Can SLS help with health condition monitoring of disturbed forest stands?

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Introduction:
Climate changes and increasingly frequent forest disturbances might cause large-scale deterioration of health condition, which can even lead to dieback of forest ecosystems. Such processes result in changes of horizontal and vertical structure of forest stands (canopy cover openness, defoliation, degradation of tree crown). Satellite Laser Scanning (SLS) missions such as GEDI (Global Ecosystem Dynamics Investigation; NASA) and ICESat-2 (Ice, Cloud and land Elevation Satellite; NASA) provide global measurements of forest spatial structure. SLS data has been widely used to derive products focused mainly on forest height and biomass estimation, but it also offers robust metrics describing vertical structure of forest stands. We hypothesised that GEDI vertical structure parameters can be used to detect differences in health condition of Norway spruce (*Picea abies* H. Karst) forest stands. Furthermore, we investigate the potential of using GEDI time series in forest health monitoring model.

Methods:
Study area covered two national parks located in the Tatra Mountains: Polish - TPN, 211.97 km^2 and Slovakian - TANAP, 742.84 km^2. We used GEDI data comprised of L2A and L2B products acquired between 2019 and 2022 in growing season (01.06-30.09). Reference 3-D forest structure parameters were simulated based on ALS LiDAR point clouds (2020, TPN) in *gediSimulator* software to assess the accuracy of GEDI metrics. Classified (supervised Random Forest algorithm) Sentinel-2 (ESA) satellite imageries were used to derive healthy and standing dead forest stand mask for each analysed year. GEDI metrics were stratified into 5.0 m height classes and intersected with healthy and dead forest class areas. GEDI Canopy Cover (CC), Plant Area Index (PAI), Plant Area Volume Density (PAVD) and Foliage Height Diversity (FHD) parameter values were compared in health condition stratification classes. GEDI time series metrics located in dead Norway spruce stands were used to analyse changes of selected parameters over time.

Results:
Analyses conducted in 5.0 m height strata showed that PAI, CC, and PAVD were significantly different (Kruskal-Wallis test, 0.05 significance level) for standing dead and healthy Norway spruce stands. Mean values of these metrics were lower for dead stands compared to healthy forest (i.e. PAI: dead=1.61; healthy=2.31; CC: dead=38.3%; healthy=70.2%; PAVD: dead=0.025; healthy=0.087 for 20-25 m forest height class), indicating a degradation of dead forest canopy. GEDI time series analysis showed consistent decrease of CC and PAI parameters (i.e. CC: 2019=47.7%, 2020=44.2%, 2021=30.2%, 2022=23.2%; PAI: 2019=1.66, 2020=1.53, 2021=0.94, 2022=0.73), indicating dynamic decay of the forest stand.

Conclusion:
Obtained results confirm that GEDI laser beams can detect the differences in vertical structure of standing dead and healthy forest stands, as well as track its changes over time. GEDI metrics have potential to be integrated with other remote sensing data (i.e. Sentinel-1,-2; ESA) and fused in forest health monitoring model, which is still under investigation.

Modelling Seasonal Sunlight Exposure of Forest Floor Using Unmanned Aerial Laser Scanning

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The effect of three-dimensional forest structure on light availability within forest ecosystems is pivotal for forest biodiversity, shaping the composition and abundance of forest flora and fauna as well as forest microclimate. Our ongoing study employs unmanned laser scanning (ULS) to assess potential seasonal sunlight exposure of forest floor within forest research plots affected by recent natural disturbance. To do this we adopted and modified Point Cloud Solar Radiation Tool (PCSRT) of Pružinec and Ďuračiová (2022).

Data collection was streamlined using a DJI Matrice 300 RTK drone with Zenmuse L1 LiDAR camera, focusing on achieving high-density point-cloud data of forest stands both in leaf-off and leaf-on state. The PCSRT software was enhanced to support automated voxel structure generation and simulation of light transmittance on individual voxel level   The voxel light transmittance was determined by the density and character of vegetation within each voxel, where voxels with less foliage allow more light to penetrate deeper into the forest structure, while voxels fully occupied by solid woody structures may provide effective shading This approach allows for simplified ant thus computationally achievable   simulation of light conditions within larger forest scenes and relatively long time periods, e.g. (part of) vegetation season.

The study simulates solar radiation exposure across various terrains for the peak vegetation season. Outputs of the simulation represent incoming energy ($W \cdot m^{-2}$) and insolation time for each voxel. The effect of forest canopy shading relative to unobstructed ground surfacesd was also investigated. Preliminary results illuminate the differential light exposure across research plots, correlating with the diversity in canopy density.

Future phases of this research will compare our PCSRT-derived data against advanced radiative transfer models like Discrete Anisotropic Radiative Transfer Model (DART), along with plans for ground-truthing to validate the simulations. This comparative analysis and validation process are critical for refining our understanding of forest light dynamics and for contributing to evidence-based forest management practices.

This initiative not only advances our understanding of forest ecosystem light dynamics but also highlights the potential of integrating modern technologies in ecological research. The outcomes are anticipated to enrich evidence based forest management strategies in biodiversity-rich environments, leveraging the study's insights on the critical role of canopy structure in regulating ground-level light availability.

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Single vs. Multi-Sensor Approaches in UAS-based Tree Species Classification in Boreal Forests

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Boreal forests are crucial for maintaining biodiversity, offering habitats for various wildlife species, and contributing to the ecosystem's resilience. Among these, old deciduous trees, particularly European Aspen, play a pivotal role by providing unique ecological niches. However, the economic value and sparse and scattered occurrence of aspens address challenges in acquiring accurate spatial and temporal data. This gap hinders the effective planning and execution of sustainable forest management and conservation efforts. Additionally, standing dead trees play a significant role in maintaining biodiversity in a boreal forest, offer essential habitats for numerous species and serve as indicators of forest health. Therefore, precise identification and mapping of tree species and standing dead trees are essential for monitoring biodiversity and forest health.

Recent advancements in unmanned aerial systems (UAS) based remote sensing have shown promise in addressing these challenges. The capability of UAS to provide ultra-high spatial and temporal resolution imagery at a lower cost compared to manned aircraft operations makes it an efficient tool for detailed forest property assessments. The flexibility and customizable sensor payload of UAS enable rapid and cost-efficient data acquisition in forested areas, which are often inaccessible or challenging for traditional aerial survey methods.

This study aims to evaluate the accuracy of various UAS-based sensors, both individually and in combination, in classifying Scots pine (Pinus sylvestris), Norway spruce (Picea albies), birches (Betula pendula and Betula pubescens), European aspen (Populus tremula L.), and standing dead trees in boreal forests. Classifications were performed with several machine learning algorithms using spectral and structural features derived from automatically segmented LiDAR, high-resolution RGB, and multispectral photogrammetric point clouds at the individual tree level. In our approach, we evaluated data from each source independently and also supplemented LiDAR and RGB dense point clouds by integrating information from NIR and RedEdge bands of multispectral imagery. For the analysis, 1,250 trees were measured in the field, with 250 trees representing each species class. Of these, 70% were allocated for training the model, while the remaining 30% were used for validating the results.

Preliminary results show promising potential in merging multispectral data with dense point clouds for effective classification of main tree species in boreal forests and will significantly contribute to the current body of knowledge by providing insights into optimizing UAS-based remote sensing for forest biodiversity monitoring. This research underscores the need for innovative approaches to support sustainable forestry practices and conservation strategies effectively.

Quantifying landscape fragmentation impacts on aboveground biomass in the Brazilian Atlantic Forest using NASA's GEDI

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Forest ecosystems where intense anthropogenic occupation has occurred are often characterized by small and isolated forest patches scattered throughout the landscape. Anthropogenic pressure and microenvironment conditions in forest remnants can potentially make forest succession difficult and limit forest's' carbon stock potential. It is well known that one of the first consequences to tropical forests under severe deforestation and degradation pressure are losses in aboveground biomass (AGB). However, AGB fragmentation has not been comprehensively assessed at large scales in tropical ecosystems and our goal was to quantify these effects.

Our study was carried out in the Brazilian Atlantic Forest which is one of the most fragmented forest ecosystems in the world, where more than 80% of the vegetation exists in patches < 0.5 km^2. We first segmented the Atlantic Forest biome into landscape units of 10 km^2. These units were then classified into natural, mixed, and anthropogenic, based on MAPBIOMAS, a Landsat-based land use and land cover classification product. MAPBIOMAS forest class was used to identify forested areas and calculate patch-level metrics related to their size, form, density, and connectivity within the landscape unit. AGB within the landscape units was quantified using L4A product data from NASA's Global Ecosystem Dynamics and Investigation (GEDI). Finally, we determined the relationship of landscape fragmentation and AGB with a suite of machine learning and regression approaches including normalized average, normalized weighted average, k-means cluster, random forest, and linear regression.

Our preliminary results suggest intact landscape units have an overall AGB ~26% greater than highly fragmented landscapes. This difference can reach up to ~37% when comparing AGB within anthropogenic and natural landscapes. Testing different approaches also indicates patch-level metrics vary in importance when assessing fragmentation impacts in AGB. Ultimately, our results can provide insights about Brazilian Atlantic Forest landscape characteristics that can be managed to support reforestation and preservation goals aiming to optimize AGB and carbon stock potential.

Early Detection of Myrtle Rust on Pōhutukawa Using Indices Derived from Hyperspectral and Thermal Imagery

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Myrtle rust is a very damaging disease, caused by the fungus Austropuccinia psidii, that which has recently arrived in New Zealand and threatens the iconic tree species pōhutukawa. Canopy level hyperspectral and thermal images were taken repeatedly within a controlled environment, from 49 inoculated (MR treatment) and 26 uninoculated (control treatment) pōhutukawa plants. Measurements were taken prior to inoculation and six times post-inoculation over a 14-day period. Using indices extracted from these data, the objectives were to (i) identify the key thermal and narrow-band hyperspectral indices (NBHIs) associated with the pre-visual and early expression of myrtle rust and (ii) develop a classification model to detect the disease. The number of symptomatic plants increased rapidly from three plants at 3 days after inoculation (DAI) to all 49 MR plants at 8 DAI. NBHIs were most effective for pre-visual and early disease detection from 3 to–6 DAI, while thermal indices were more effective for detection of disease following symptom expression from 7 to –14 DAI. Using results compiled from an independent test dataset, model performance using the best thermal indices and NBHIs was excellent from 3 DAI to 6 DAI (F1 score 0.81–0.85; accuracy 73–80%) and outstanding from 7 to –14 DAI (F1 score 0.92–0.93; accuracy 89–91%).

Estimating and mapping forest age across Canada's forested ecosystems

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Introduction/Aim:
Accurate knowledge of forest age is a critical input variable for carbon modelling, forest management, and for assessments of habitat and biodiversity. Conventional estimates of forest age are typically derived through tree coring, or photo-interpreted from aerial imagery. However, both methods are typically sample or plot-based, and spatially-explicit maps of forest age are usually not made over very large areas. For regional to national monitoring and land-management decisionmaking purposes, wall-to-wall, spatially explicit maps of forest age are desirable.

Remotely sensed satellite data, such as from Landsat, has allowed for the creation of wall-to wall maps of land cover and stand-replacing forest disturbance from 1985 onwards. However, due to the limited temporal range of these datasets, and the relative infrequency of disturbance, they only allow for the estimation of age within the past few decades, and other methods for estimating forest age are required for a fuller understanding of forest age dynamics.

Methods:
This research combines three approaches to estimate forest age across Canada at 30-meter resolution from 0-150 years with an older than 150 class. The first method avails upon existing change detection methodologies to detect pixels which were disturbed between 1985-2019, using time since disturbance as a proxy for forest age. The second method uses Landsat surface reflectance composites to track the spectral trajectory of pixels in the early Landsat record, and identify any which show evidence of recovering from a disturbance which happened before the Landsat record, extending age estimates to 1965. The last method combines Landsat-derived maps of tree species and height with productivity metrics and existing allometric equations to estimate forest age for pixels which show no evidence of disturbance within the satellite record, recognizing that as age increases, so too does uncertainty in age estimates.

Results:
By combining these three approaches, age is estimated for every treed pixel in the forested ecoregions of Canada, accounting for 650 Mha. Nationally, mean estimated forest age for forests less than 150 years old (94.1% of treed area) was 70 years, with a standard deviation of 32.1 years. Forest age estimates were compared to reported forest age in the Canadian National Forest Inventory (NFI) both spatially and aspatially. Nationally, 5.9% of the forested area was estimated to be older than 150 years, compared to 9.5% of area within in the NFI sample. Median estimated forest age for forested pixels ≤150 years old was 68 years, while median forest age reported in the NFI was 73 years. Regional variability was present in results, with lower agreement found in areas characterized by older forests.

Conclusion:
Accurate and spatially explicit maps of forest age are a useful tool for land management, forest monitoring, carbon modelling, and other scientific endeavours. The results found in this work provide a useful basis for a variety of these activities in Canada, and the methodologies utilized are portable to other areas where similar base datasets exist.

An innovative operational strategy for forest attribute mapping and per-pixel error estimation within a design-based statistical approach coupling remote sensing and field data

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Reliable information about forest ecosystems is critical and the role of remote sensing in acquiring information has been debated by long time. Although remote sensing has made enormous progress in recent decades and map products derived from remotely sensed data are increasingly available, quality indicators and uncertainty estimates are lacking or achieved from models based on questionable assumptions. Therefore, clearer and more transparent validation and uncertainty estimation of maps remain major challenges in remote sensing of forests. Here we present dataDriven (https://github.com/saveriofrancini/dataDriven), an open access strategy that leverages cloud computing (Google Earth Engine) and high-level programming language (R) capabilities to enable users to easily produce maps of forest attributes and maps of the associated per-pixel error within a specific area of interest. This strategy uses a data-driven design-based statistical approach and relies on Sentinel-2 remote sensing data as auxiliary information, avoiding the need for extensive modeling associated with model-based approaches. Ground reference data must be available for a sample selected by simple random sampling, one-per-stratum stratified sampling or systematic sampling. A unique aspect of our operative strategy is the generation of both the attribute map and the corresponding map of estimated precision. This allows users to make informed spatial assessment of the attributes under investigation.

105

Analysis of dense optical time series for the spectral and temporal characterization of bark beetle attacks.

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Recent years have seen an increase in the frequency and severity of disturbances[1], with 17% (39 million ha) of Europe's forested areas affected between 1986 and 2016[2]. Accordingly, it is important to better understand disturbance dynamics to 1) define forest management practices to improve resilience; 2) improve reaction and mitigation strategies; and 3) develop better detection algorithms based on remote sensing data. Disturbance monitoring with remote sensing has been widely addressed, even though most of the focus has been devoted to stand replacing disturbances. Existing works focused on non-stand replacing disturbances (NSRD), often considered only yearly composites [3,4]. With Sentinel-2 and other constellations in orbit for several years, time series with unprecedented combined spatial and temporal resolutions spanning several years have become widely accessible. Consequently, it is now possible to characterize NSRD at a monthly or higher temporal resolution on a large scale.

The aim of this work is to explore the temporal and spectral patterns of bark beetle attacks by analyzing Sentinel-2 time series. To this end, 500 30x30m areas attacked by bark beetles were sampled in the Trentino province, northern Italy, from existing disturbance maps[5]. For each attacked area, 25 points were randomly sampled in healthy forest at 20 m from the border of the attack, for a total of roughly 12000 samples. This was to provide reference spectral values for comparison and to standardize the spectral trajectories of the affected areas relative to their environmental context. For each area, we computed the spectral trajectory of 3 spectral indexes: Normalized Burned Ratio (NBR), Normalized Difference Moisture Index (NDMI) and Normalized Difference Vegetation Index (NDMI). Then, we estimated the start and end dates and magnitude of attack using the 3 indexes. Start and end dates were estimated as the first dates when the spectral index surpassed a threshold (two separate thresholds for start and end of attack) for all the remaining of the series. Results showed that the NDVI allows for the detection of the start of the attack slightly earlier with respect to the NBR and NDMI. In contrast, the end of the attack is detected in average 10 days earlier with NBR and NDMI compared to the NDVI. Regarding attack magnitude, NBR and NDMI showed the highest average values (0.49 and 0.48) compared to NDVI (0.38).

Accordingly, in the second part of the analysis, only the NBR was considered. For each point, we considered the elevation, and we estimated the daily minimum, maximum and mean temperature by kriging spatial interpolation of field meteorological stations data. Preliminary results showed that elevation is weakly correlated to attack duration and magnitude. In contrast, temperature showed a correlation with both attack duration and magnitude. As the average temperature during the attack increases, the attack duration decreases while the magnitude increases. Moreover, we also analyzed the thermal sum in the period prior to the attack. Results showed that as elevation increases, the thermal sum required for the start of the attack decreases.

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Imaging spectroscopy for bark beetle detection in Norway spruce and the relevance of the red-edge spectral range

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In this study, hyperspectral data of two geographically distant study areas in Germany were analyzed to find the most effective spectral wavelengths for red-edge-based vegetation indices to differentiate bark beetle-infested Norway spruce into three infestation classes, including green-attack. Considering that the relationship between red-edge position (REP) and reflection shoulder position (RESP) is crucial for the relative quantification of chlorophyll concentration and LAI and their changes due to bark beetle infestation, we tested normalized difference red-edge indices (NDRE) formed from these parameters. Using the second derivative method, the REP calculation resulted in an average value of the infestation classes of 715.14 nm and 715.81 nm (both corresponding with the 716 nm band of the camera) for the two independent study sites, the RESP wavelengths were 759.35 nm (camera band 758 nm) and 760.4 nm (camera band 761 nm), respectively. Furthermore, using combinations of 75 spectral bands in the range 685 nm to 850 nm, we formed and analyzed 1187 different NDREs, and two additional vegetation indices, and show that the sorted, normalized Kruskal-Wallis H-value, followed by a frequency analysis of the RESP and REP bands of the 10% of the highest ranked NDREs is an effective way to identify the global optima of these parameters. The optimal REP and RESP estimated using this approach were determined at 714 nm and 758 nm, respectively. The derived normalized difference red-edge index $NDRE_{758\_714}$ could be successfully applied to both test sites. Moreover, we found that aggregating hyperspectral bands into broader bands - 703 nm to 729 nm for a REP band and 741 nm to 767 nm for a RESP band - did not degrade model accuracy when used in a multispectral NDRE, suggesting that a hyperspectral camera is not required to perform the task. Multinomial logistic regression (MNLR) and random forest (RF) classification models were successfully transferred between the two geographically distant study sites. The predictive accuracies of the models for the test data indicated MNLR to be more robust than the RF. With the MLNR models applied, overall accuracies 77.4 % were achieved in the first study area imaged during the green-attack core period, and 88.5 % in the second study area imaged at the final green-attack stage. Our results contribute to forest health monitoring with imaging spectroscopy data and provide practical recommendations for sensor design with broader bands.

Enhancing tree-list maps by incorporating end-user preferences of remote sensing products

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Introduction/Aim:
Distance independent growth and yield models, along with fire spread engines rely heavily on detailed, spatially explicit inputs provided by tree lists maps. By leveraging tree lists, numerous attributes crucial for various forest management tasks can be calculated. However, prioritizing one attribute during model selection for tree list prediction may lead to poor performance. This issue becomes apparent when the modelled tree lists are used to derive other equally significant attributes relevant to forest management. To address this challenge, we propose refining the model selection process for tree list prediction by incorporating the forest attributes that final users deem most important, and also considering the relative importance or weight assigned to these attributes by users.

Methods:
We conducted an extensive study to identify the key variables essential for refining model selection in tree list prediction. To achieve this, we directly engaged with end users of the tree lists maps, soliciting their insights on the forest attributes critical for their work. Users were asked during interactive surveys administered both in the Western US (Meddens et al. 2022) and Spain. Results from these surveys were used to identify both the most important attributes for end users and their relative importance. Then, we fitted and compared imputation models to predict tree lists by: 1) optimizing the model performance for each of the identified attributes alone, and 2) optimizing the model performance of a weighted average of all identified attributes. For the second alternative, attributes were weighted according to the importance reported by the end users in the interactive surveys.

Results:
In both the Western US and Spain, optimized models for a single attribute resulted in tree lists with a very poor performance for other important attributes highlighted by forest managers. This issue was especially pronounced in the Western US with models optimized for basal area (BA) and mean tree height (MTH). Specifically, trees lists derived from optimized BA models depicted a root mean square error (RMSE) for MTH that was 76.86% higher than the RMSE obtained from MTH optimized models. This model selection strategy showed that by integrating the attributes' weights reported by end users in the model selection process, it was possible to obtain tree lists maps that: 1) were more balanced for all attribute and 2) had only moderate loses in performance with respect to models optimized for a specific attribute.

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Constraining estimates of Boreal vegetation productivity in multi-source remote sensing-based models

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Introduction/Aim:
The global boreal ecosystem covers 1.9 billion hectares and is estimated to sequester 8.9 billion tonnes of carbon annually. Conventional model estimates of carbon dynamics are produced at coarse spatial resolutions leaving the heterogeneity of boreal landscapes and their carbon dynamics poorly represented. Due to rapid environmental changes in these regions, robust and comprehensive models for Gross Primary Productivity (GPP) of terrestrial vegetation in boreal environments are needed at finer spatial and temporal scales than are currently available. Advances in remote sensing technologies allow for refined representation of fine-scale patterns in GPP and offer new opportunities for improving current predictions by addressing known sources of uncertainty. Notably, key drivers of boreal GPP can now be represented through modern estimates of Land Surface Temperature from Sentinel 3, Soil Freeze/Thaw and Soil Moisture conditions from the Soil Moisture Active Passive (SMAP) platform, and vegetation vigour from Harmonized Landsat Sentinel-2 (HLS). In addition, modelling frameworks such as the National Terrestrial Monitoring System can now provide fine-scale information on boreal land cover types and disturbance histories, which allows for the stratification of model estimates across large areas while accounting for landscape heterogeneity. The focus of this work is to bring together these disparate pieces of information on the drivers of boreal productivity from innovative satellite products to improve model estimates of GPP and provide comprehensive insight into its drivers under changing future climates.

Methods:
Through data fusion, the spatial and temporal resolutions of the aforementioned datasets are resolved to allow for their integration into a new model of GPP. Land cover and fire disturbance history information is used to stratify relatively homogenous areas across the Canadian boreal. For these stratified areas, Land Surface Temperature, Soil Freeze/Thaw, Soil Moisture, and vegetation vigour (Enhanced Vegetation Index) are combined into an estimate of GPP. These estimates are then parameterized using a selection of reference productivity datasets and are predicted and validated across key boreal land cover types.

Results:
Model estimates of GPP using our new model framework were able to achieve high correlations with reference productivity datasets ($r^2 > 0.9$) across stratified areas dominated by key boreal land cover types such as wetlands, treed-wetlands, and coniferous vegetation. Model estimates were also produced for sites representing unique fire disturbance histories, and achieved similarly high correlations with reference products. Compared to conventional remote sensing-driven model estimates generated for reference, sum of squares errors (SSE) were reduced by > 50%.

Conclusion:
Compared to prior work, model estimates of GPP were generated with markedly reduced seasonal biases. In addition, the use of fine-scale land cover and disturbance information allowed for more accurate parameterization of model estimates across heterogeneous land cover types than other satellite-based estimates of GPP. Overall, the new model framework provides comprehensive information on boreal vegetation productivity and its drivers with improved representation of spatial heterogeneity and seasonal trends in GPP. Through these improvements, our model provides valuable insight into the carbon dynamics of key boreal environments commonly underrepresented in existing model frameworks.

A study on pine wood nematode disease monitoring based on UAV-based remote sensing and machine learning in a mixed forest of central China

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Introduction/Aim:
Pine wood nematode(PWD) is a devastating disease of pine trees, seriously threatening the ecological security of China's forests. Timely and reliable monitoring of PWD is extremely important for forest management and disease prevention and control. However, as PWD spreads quickly, traditional manual survey methods are difficult to meet the demand. UAV-based remote sensing can quickly and accurately obtain the spatial distribution and extent of forest pests and diseases, providing reliable information support for forest pest control and management.

Methods:
In this study, a DJI UAV was used to acquire high-resolution red-green-blue (RGB) visible images. Then, vegetation indices (VIs) and texture features (GLCM) were calculated, and a feature selection algorithm was used to select optimal feature combination. After that, Random Forest (RF) and Support Vector Machine (SVM) algorithms were used and compared to monitor the severity degree and spatial distribution of PWD.

Results:
The results showed that (1) using vegetation indices were better than those using texture features; (2) the combination of vegetation indices and texture features can significantly improve the monitoring accuracy; (3) the classification performance of SVM algorithm was better than that of RF.

Conclusion:
UAV-based remote sensing can provide timely and reliable PWD information for forestry pest control and maintaining ecological security.

Development status of Spaceborne Lidar MOLI

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Global forest biomass (AGB) observation by remote sensing is practical for estimating the effects of climate change caused by human activities, future climate projections, biodiversity, and resource abundance. One of the AGB monitoring methods is the radio wave observation method, which includes the ALOS/PALSAR series (Phased Array type L-band Synthetic Aperture Radar). This method has a problem: the observed signal is saturated, and the accuracy is degraded when forest biomass exceeding 100 t/ha is observed. Unlike radio wave observations, space-based LIDAR observations are spatially discrete but can measure tree height and biomass with high precision.

JAXA is planning to launch the Multi-Sensing Observation Lidar and Imager (MOLI) mission aboard the ISS Kibo Exposed Section in 2028. This mission will perform waveform-recording lidar observations using lasers with a power output of 5W or more and panchromatic band imager observations in addition to Green, Red, and NIR. Panchromatic band observations can record characteristic textures not only in daylight but also in urban areas and artificial objects at night so that the imager observation data and the reference image with coordinates will be used for image matching to correct the lidar observation coordinates and to measure the forest canopy term and AGB with high accuracy. In addition, analysis using observation data from the previous GEDI mission and Aerial Laser Survey (ALS) data revealed that the accuracy of ground surface estimation from LIDAR waveforms is affected by the accuracy of forest canopy height and AGB estimation, and we are developing a ground surface estimation algorithm using deep learning to solve this problem.

In this presentation, we will report on the current MOLI mission equipment, the specifications of the products to be released, the development status of the ground surface estimation algorithm currently under development, and the correction of the accuracy of lidar observation location determination by image matching.

Mangrove conservation, ecotourism and blue carbon markets in the Asia-Pacific: Exploring links using remote sensing

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This study examines the links between mangrove conservation, ecotourism and blue carbon markets in the Asia-Pacific region using remote sensing. By combining literature review findings with remote sensing data — such as satellite imagery, space-borne LiDAR, and SAR — and advanced analytical techniques, we evaluate how mangroves contribute to carbon sequestration and support sustainable tourism. Our analysis highlights key factors that affect the success of blue carbon and ecotourism projects, and their impact on local economies and conservation efforts. We present successful case studies and suggest remote sensing-based strategies for better integrating mangrove conservation with ecotourism and carbon markets. This research aims to offer actionable insights for policymakers and stakeholders to boost the sustainability and economic value of mangrove ecosystems in the region using remote sensing.

A high spatial resolution land surface phenology dataset for AmeriFlux and NEON sites

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Introduction/Aim:
Vegetation phenology is a key control on water, energy, and carbon fluxes in terrestrial ecosystems. Because vegetation canopies are heterogeneous, spatially explicit information related to seasonality in vegetation activity provides valuable information for studies that use eddy covariance measurements to study ecosystem function and land-atmosphere interactions.

Methods:
Here I present a land surface phenology (LSP) dataset derived at 3 m spatial resolution from PlanetScope imagery across a range of plant functional types and climates in North America.

Results:
The dataset provides spatially explicit information related to the timing of phenophase changes such as the start, peak, and end of vegetation activity, along with vegetation index metrics and associated quality assurance flags for the growing seasons of 2017–2021 for 10 × 10 km windows centred over 104 eddy covariance towers at AmeriFlux and National Ecological Observatory Network (NEON) sites.

Conclusion:
These LSP data can be used to analyse processes controlling the seasonality of ecosystem-scale carbon, water, and energy fluxes, to evaluate predictions from land surface models, and to assess satellite-based LSP products.

Investigating growth response to drought in a boreal forest using permanent sample plots, Landsat time series and airborne laser scanning data

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Amidst increasing uncertainty surrounding the productivity of forest ecosystems under climate change, timely and accurate information on forest condition is critically important. Capitalising on the known relationships between spectral indices and the physiological responses of trees, several studies have utilised satellite imagery data to investigate changes in canopy condition. Although the possibility to detect and characterize abrupt changes due to disturbances and mortality has been widely demonstrated using various satellite-based sensors, observing the latent effect of climate change on forest growth remains a challenge due to its gradual nature. The current changes in temperatures and precipitation regimes are generating pervasive but heterogeneous responses across forest ecosystems, with the effects on canopy spectral reflectance only becoming noticeable after several years of observation. In boreal forests, there is growing evidence that water deficits caused by warmer summer temperatures are leading to decreases in the growth rate of some species, influenced by multiple factors such as stand development stage, structural attributes, and site characteristics. While this phenomenon has been observed in a variety of studies involving the analysis of tree rings and permanent sample plots (PSPs) data, our understanding of its extent and magnitude at the scale of the Canadian boreal forest remains largely unknown. The objective of this study was to develop spatially explicit estimates of net forest growth rates over a forest management unit in Canada using Landsat time series data, and to examine the changes in predicted growth rates during a period of repeated drought episodes. We also examine how the observed changes are related to forest structure and site characteristics derived from airborne laser scanning (ALS) data.

Data from Landsat time series and PSPs was first used to develop estimates of annual net basal area growth over the study site from 1984 to 2021 at a 30m spatial resolution. Predictions were generated for ten-years moving windows with an ordinary least square regression model developed using data from 120 PSPs and validated on an independent set of 60 PSPs, with R2 values of 0.61 and 0.58, respectively. Applying the model over the 586,607 ha study area revealed considerable temporal and spatial variability in the predicted growth rates and their evolution through time. We then specifically examined the growth response to abnormally dry years recorded between 2001 and 2010 by comparing the predicted growth rates in the 10 years prior to drought periods, during the 10 years when droughts occurred, and in the 10 years following the last recorded drought event. Using these variables, we conducted a spatial segmentation of closed-canopy forests within the study site to delineate areas with homogeneous growth responses to the repeated drought events. We then examined how the growth response varied considering the structural attributes of forests in the delineated segments and site characteristics derived from ALS data. The results provide a better understanding of the effect of environmental stress on forest growth and offer a means to identify target areas where silvicultural interventions aimed at maintaining or enhancing growth could be conducted.

deadtrees.earth - an open database to bridge drone and spaceborne imagery for tree mortality mapping

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Excess tree mortality in the wake of climate extremes has been observed globally. We are currently limited in understanding the mechanisms of tree mortality, as we lack tools and datasets to assess the spatial and temporal patterns of tree mortality at continental scale**.**

Multispectral data of the Sentinel-2 satellites mission cover the entire globe on average every five days at a finest spatial resolution of 10 m. One requires high-quality, in-situ reference data to detect tree mortality from Sentinel-2 imagery. However, standard forest inventories are rarely publicly available, have limited information on tree mortality, and are challenging to align with raster images.

Consumer drones offer a way to obtain orthomosaics which clearly depict dead trees. Furthermore, with the increased user-friendliness and decreasing cost of drones, high-resolution imagery of forests is now becoming widely available. Detecting tree mortality in such generated orthophotos has become a classic segmentation task. Those dead tree segments can be extrapolated to the Sentinel-2 10 m raster and have successfully been used as training data to infer tree mortality from Sentinel-2 data in German forests (Schiefer et al., 2023).

In this study, we aim to create a global database for tree mortality orthophotos and annotations and that acts as reference data to build a model that can globally detect deadwood in Sentinel-2 imagery. Such an ambitious scale introduces several challenges, such as computational cost, but most notably, the demand for an enormous collection of diverse high-resolution orthoimagery across all tree ecosystems. To obtain such a collection we rely on community contributions. This work makes the following efforts:

1) We present an open database of RGB orthoimagery of forests with a focus on high-resolution imagery with more than 10 cm resolution. deadtrees.earth launches with more than 1000 orthophotos from almost 20 countries through the collaboration of almost 30 research institutions and aims to grow into the state-of-the-art database for remotely sensed tree mortality.

2) We developed a CNN-based segmentation framework for delineating standing deadwood across image resolutions and forest ecosystems, which can be applied to any RGB orthophoto and is offered to users as a service.

3) We created a transformer-based model that identifies the fractional cover of standing deadwood across forest ecosystems through Sentinel-2.

Modernization and transformation of Lithuanian National Forest Inventory: the role of remote sensing

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Introduction/Aim:

The Lithuanian National Forest Inventory (NFI) has evolved into a primary data provider for numerous national and international forestry stakeholders over the last quarter-century. Incorporating data collection for greenhouse gas reporting in the Land Use, Land Use Change, and Forestry sector (LULUCF) a decade ago transformed the Lithuanian NFI into a multidisciplinary activity. Methodologically, the Lithuanian NFI adheres to principles developed several decades ago, employing systematic sampling that includes measurements on more than sixteen thousand plots and relies heavily on human field measurements. However, ongoing efforts are being made to update the inventory to align with current international and national legal frameworks, particularly in upgrading the sampling scheme to facilitate wall-to-wall mapping of both land uses and forest land attributes. The presentation aims to introduce the latest developments of the Lithuanian NFI and its adaptation to the current international and national legal framework, focusing primarily on the enhancement of the sampling scheme to enable comprehensive mapping of land uses and forest land attributes.

Methods:

The sampling design is founded on the potential of remote sensing to identify historical land use conversions and the evolution of forest land attributes. Although airborne laser scanning data serves as the primary information source, other forms of remotely sensed data, particularly those available for historical periods, are integrated and verified alongside GIS datasets associated with land use or land cover. Initially, land use types are identified across a network of virtual sample plots distributed throughout the entire country at 25x25-meter intervals. This process combines information sourced from spatial databases with data derived from airborne laser scanning, airborne orthophotos, and satellite images to justify specific land use classifications. Subsequently, the grid of virtual sample plots is refined to a resolution ranging from 5x5 to 12.5x12.5 meters for forested areas to accurately characterize their dendrometric properties, leveraging remote sensing techniques and data from the NFI permanent field plots. Furthermore, a modeling approach to reconstructing past land use development is applied. This involves utilizing historical land use data from NFI permanent plots and earlier versions of spatial data, supported by historical remote sensing imagery, as inputs for machine learning algorithms.

Results:

Operational guidelines for new Lithuanian NFI starting from 2025 are elaborated and validated. Additionally, examples demonstrating the improved Lithuanian NFI for updating the State forest cadastre, facilitating private forest management planning, and supporting carbon farming initiatives are provided.

Conclusion:

The suggested approach could be applied for wall-to-wall mapping of current land use and the reconstruction of past land use and forest dynamics. This contribution aids in developing a comprehensive understanding of landscape evolution over time, particularly as part of continuous forest monitoring and sustainable management efforts aimed at delivering multiple ecosystem services.

227

Benchmarking under- and above-canopy laser scanning solutions, including autonomous drones, for deriving tree attributes in boreal forests

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Introduction:
Detailed information regarding forests is required for utilizing them for economic purposes, while simultaneously maintaining biodiversity and their carbon sink properties [1]. For this purpose, individual-tree-level forest inventories are needed. Such inventories require accurate field reference for main tree attributes (diameter, volume, height and location), and should be fast to collect from a large area.

In this study, we compared the accuracy of the tree attributes and location automatically derived from point clouds of several laser scanning systems, operating both under- and above the forest canopy to provide this reference.

Methods:
The benchmark was performed on test sites located in Evo, Finland. Six $32x32$ m plots were used for the tree attribute benchmark, and a 800-m-long positioning track for evaluating the accuracy and precision of the positioning. The forest conditions varied from sparse, managed boreal forest mainly consisting of Scots pine (*Pinus sylvestris*) to dense natural boreal forest with a mix of coniferous and deciduous trees. The plots were categorized into easy and difficult plots based on the tree density and tree composition.

We utilized an automatic tool [2] for deriving the tree attributes and location, along with a novel bias compensation method to calibrate out the bias caused by the finite width of the laser beam.

We compared several state-of-the-art mobile laser scanners (MLS) operating under the forest canopy, and an airborne laser scanner (ALS) flying approximately 100 m above the canopy. The MLS systems included handheld devices and autonomous under-canopy drones, both in-house developed and commercial.

Results:
The positioning accuracy and precision (RMSE) of the ALS was <5 cm horizontally, and <10 cm vertically. The positioning precision of MLS devices were approximately 15 cm for the full positioning track and 5-15 cm for a half-track.

For the best performing MLS systems, the accuracy of the derived tree attributes; stem curve, diameter at breast height (DBH), stem volume and tree height ranged from 5–10 % RMSE for all attributes except for tree height and volume in the densest plots, with high understory vegetation, where the error was approximately 20 %. The accuracy of high-density ALS data was 10–25 %. The bias compensation reduced the bias of the tree diameter estimates by 55–99 %.

Conclusion:
The positioning accuracy and precision of high-density ALS was equal or better than the traditional field reference collected with a total station, while being orders of magnitude faster to collect from a large area, and thus can be used as a reference in future studies. The precision of the under-canopy laser scanners were also sufficient to unambiguously distinguish neighboring trees, which is required for use in an individual-tree-level forest inventory. However, their ability to localize themselves in a global frame was lacking.

The accuracy of the derived tree attributes from the most accurate under-canopy laser scanner systems were sufficient for use as a reference for individual-tree-level inventories (<10 % RMSE). The laser scanners with high beam divergence (and ALS) did not reach the required accuracy even with the help from the bias compensation.

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Estimating the integrated and individual impacts of the human footprint on forest ecosystem structure and function.

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Anthropogenic pressures on forested ecosystems are globally increasing, leading to marked impacts on biodiversity and ecosystem services. There is a need to assess to what degree the human footprint, a measure of anthropogenic pressures such as population density, roads, and industrial activity, influences forest biodiversity metrics. This would allow management and policy makers to locate heavily impacted areas in need of ecological restoration or high-quality unimpacted areas which could be suitable for integration into the protected area network. Satellite-informed datasets on forest structural and functional attributes, as well as measures of the human footprint on the environment, are becoming available at increasingly finer spatial scales.
Here, we describe a new methodology to assess the impact of human footprint on forest structure and function via its combined and individual components. Focusing on British Columbia, the province with the largest environmental gradients in Canada, we use forest structural attributes imputed from airborne lidar data and Landsat imagery including canopy height, cover, structural complexity, and aboveground biomass. We also focus on the Dynamic Habitat Indices (DHIs), including the cumulative, minimum, and variation in energy available throughout the year.
We used impact evaluation techniques to match all pixels in the province with unimpacted counterfactuals based on similar terrain and climate. We calculated forest structure and function reference states for unimpacted areas (protected pixels with low human footprint score) using a bootstrapping approach and assessed how varying human footprint components impact forest structure and function. This approach allows for the identification of both relatively unimpacted forest areas and their respective attributes, as well as the relative changes in traits associated with increasing human footprint.
Results indicate that the combined pressures of the human footprint are greater than the sum of the individual pressures. As the combined human footprint increases, the distance from the reference state for forest structural traits increases, while forest ecosystem function generally remains similar to the reference state. We also demonstrate that the method presented herein allows for the complete spatial reconstruction of matching outcomes. This facilitates protected area managers to identify locations with traits in need of restoration (outside the reference state and heavily impacted by anthropogenic pressures) or protection (within the reference state with low/no anthropogenic pressures), thereby improving the capacity for management.

13

Continuous update of Enhanced Forest Inventory attributes with optical time series data

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Introduction/Aim:
Detailed and up-to-date forest inventories are critical in informing sustainable forest management decisions. One method of deriving spatially explicit maps of forest attributes is to combine airborne laser scanning data with field measurements to generate an Enhanced Forest Inventory (EFI), which can provide wall-to-wall characterizations of key forest attributes. Although providing a high level of spatial and structural detail, EFIs represent a single point in time and thus are not capable of characterizing changes in forest attributes, a need that is becoming more important given uncertain future conditions and increasing disturbance frequencies and intensities. To address this challenge, we investigated how a time series of optical satellite data could be used to update an EFI generated for a large (~690,000 ha) forest management unit in Ontario, Canada, at an update interval of every 2 weeks.

Methods:
The approach involved two distinct phases. In the first phase, a time series of Harmonized Landsat Sentinel-2 data were downloaded and variables characterizing the intra-annual amplitude, slope, and trend of 14 spectral bands and indices were calculated. Next, models were developed to impute 7 commonly derived EFI attributes: aboveground biomass, basal area, stem density, Lorey's height, quadratic mean diameter, and stem volume using a k-Nearest Neighbour (kNN) model with the spectral metrics as the response variables. The study area was split into 20 strata representing all combinations of species groups and site productivity classes, and a kNN model per stratum was created. In Phase 2, the same spectral variables were derived at 2-week intervals for the 3-year period following the EFI acquisition. The models developed in the first phase were applied to key stands of interest and imputed attributes were observed through time to investigate the application of the models to stands experiencing both disturbances and growth (i.e., no disturbance).

Results:
Across all strata, models were generally accurate, with relative RMSE ranging from 11.47% (canopy cover) to 31.82% (stem volume). While there were generally no patterns of how accuracy varied across species groups, attributes for more productive site classes were typically predicted with greater accuracy than attributes for low-productivity sites. In the application to future periods (Phase 2), models were able to capture the stand dynamics of the focal sites in the study area. Outputs from this second phase demonstrated the potential of the approach for characterizing changes in EFI values in areas experiencing no change or non-stand replacing disturbances.

Conclusion:
A timely and detailed forest inventory is critical to sustainable forest management. In order to keep up with highly dynamic future conditions, new tools and techniques need to be tested in order to understand how they can be integrated into managing the forests of the future. This study demonstrated an approach to update EFI attributes at any temporal interval, thereby promoting near-real time integration into forest management and enabling more informed decision-making to prescribe treatments or understand the state of forest resources under uncertain future conditions.

Estimating Green and Teal carbon stocks across the Gauteng Province of South Africa using a multi-source remote sensing approach

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Introduction/Aim:
Cities across the globe are known to emit more carbon than they sequester and store. To reduce the impact of climate change, cities, governed by their climate action plans and international climate programs, have sought to reach carbon neutrality. To reach this goal, a detailed inventory of carbon sinks and sources is required at the highest possible measuring unit. Remote sensing technologies, coupled with representative calibration and validation datasets and machine learning upscaling approaches, have been considered vital tools for carbon accounting. This study sought to quantify green (i.e. tree and grass carbon) and teal (i.e. from wetland vegetation) carbon stocks across the built-up province of Gauteng South Africa, using multi-source (field data, airborne LiDAR, L-band ALOS-2 PALSAR-2, C-band Sentinel-1 and Sentinel-2) remote sensing datasets within a Random Forest machine learning environment.

Methods:
Land Use Land Cover and national wetland inventory datasets were used to mask out the urban footprint, rivers and open water bodies. Green carbon estimates were predicted based on an approach, which estimated vegetative above-ground biomass (AGB) by upscaling ground-measured AGB (via allometric measurements and equations) to regional airborne LiDAR data, and then upscaling to the satellite scale using integrated ALOS-2 PALSAR-2 L-band SAR and Sentinel-2 derived RENDVI vegetation index datasets. Teal carbon estimates were predicted based on an approach, which estimated herbaceous AGB by upscaling localised ground-harvested (and dried) wetland AGB (together with in-field measured leaf area index measurements) directly to spaceborne Sentinel-1 backscatter and Sentinel-2 reflectance bands. For the modelling approaches, Random Forest (RF) machine learning models were trained to predict green and teal AGB and subsequently carbon at the resampled spatial resolution of 25m. Model accuracies were documented using validation statistics such as R^2 and RMSE. AGB was converted to carbon using a conversion factor of 0.5.

Results:
Using a 35/65% calibration and validation dataset split, the RF yielded a validation accuracy of R^2 = 0.74 and RMSE = 12.17t/ha (AGB) for the green carbon model. A higher quantity of green carbon was found in the peripheral areas outside the main cities than within the city limits. The northern half of the Gauteng province contained more stored green carbon than the southern half. Greater densities of green carbon were also found within protected areas of the province (50 MgT/ha). The overall green carbon stock in Gauteng was estimated to be 488.8 MgT/ha. Preliminary results of the teal carbon RF model (using a 65/35% calibration and validation dataset split) yielded R^2 = 0.65 and RMSE = 41.3 g/m^2 (AGB). The spatial analysis of this model and subsequent map is still pending.

Conclusions:
Understanding the largest share of terrestrial carbon (i.e. green carbon) and the most elusive (i.e. teal carbon) carbon sinks, coupled with updated emissions data, can help cities understand how far off they are from a carbon-neutral status.

125

Young circumboreal forest growth hotspots identified with ICESat-2 and Landsat Stand Age

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Warming in the higher northern latitudes has improved conditions for forest growth, yet the fate of aboveground biomass (AGB) in the domain remains uncertain. Forest height is a strong predictor of AGB, and spatially detailed height-age relationships could improve our understanding of carbon dynamics in this ecosystem. To our knowledge site-index, defined as the capacity of land to grow trees, has not been estimated throughout the domain. We calculated it by co-locating 5,941,072 contemporary ICESat-2 canopy height observations with Landsat stand age estimates from 1985-2020. We found strong environmental gradients of height-age relationships throughout the domain when disturbance was excluded. We then selected disturbed segments and subtracted them from site-index predictions to estimate young forest growth potential. Strong departures (>5 m height) were found clustered in Southwestern Russia and sparsely distributed throughout the domain. Our results reveal the location and potential growth of young boreal forests if regeneration occurs.

Modelling and mapping multi-layer fine fuel loads in Australian Eucalypt forests using airborne Lidar

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Fine fuels are pivotal in the spread and behaviour of wildfires, particularly in highly flammable ecosystems such as Eucalypt forests in Australia. Despite this significance, the spatially explicit mapping of fine fuels in Australian Eucalypt forests using lidar remote sensing remains scarce. Vertical complexity in Eucalypt forests creates a non-uniform distribution of fine fuels across different heights. Previous studies focusing on quantifying fine fuel loads from airborne lidar (ALS) data often concentrated on upper canopy layers and achieved low accuracies for understorey layers. Addressing these gaps, this study employs fine-scale forest structural information derived from stratified ALS data to model and map multi-layer fine fuel loads in Eucalypt forests in East Gippsland, southeastern Australia.

We initially stratified ALS point clouds into distinct vertical forest strata and computed a large set of metrics from both stratified and unstratified ALS data. These metrics were then utilised to predict forest inventory-based fine fuel variables (canopy, elevated, near-surface, surface, and total loads) using Random Forest models. The model for canopy fine fuel load demonstrated the highest accuracy, with an R^2 value of 0.83, followed by total fine fuel load with an R^2 of 0.74. Elevated and near-surface fine fuel loads were moderately well predicted, with R^2 values of 0.57 and 0.58 respectively, while the model for surface fine fuel load yielded an R^2 of 0.68. Our findings also suggest that the integration of ALS predictors from different vertical strata led to optimal model performance for all fuel variables. Although predictors from upper canopy layers exerted the most influence, metrics describing shrub and herb structures also significantly contributed by interacting with other predictors, thereby impacting prediction results. These findings elucidate the complex interplay within vertical strata, highlighting how attributes across multiple forest layers explain the variation in fine fuel loads.

We finally applied the developed models for wall-to-wall mapping of pre- and post-fire (2019-2020 season) fine fuel loads across a re-surveyed ALS area. Fine fuel consumptions were then analysed in relation to burnt severities using the derived prediction maps. Comprehensive research methods and results from this study are important to support fire management and fire behaviour modelling activities.

294

Towards Supporting Objective Forestry through Immersive Technologies

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Objective forestry management employs modern technologies such as LiDAR and other remote sensing techniques to support effective decision-making and sustainable resource management. Beyond capture, this data must be stored, recalled, processed and ultimately understood by human experts to support this effective decision-making. Immersive technologies have the potential to support this human-in-the-loop process through large-scale and immersive visualisation. This talk will present the perceptual benefits we have found to support examining forest point cloud data in Virtual Reality (VR). Over a series of pilots and user studies, we have identified a set of analogous forestry tasks that are supported in VR compared traditional display approaches. This talk will also present our roadmap for realising forest digital twins in VR to support immersive analytical decision making.

Comprehensive analysis of thirty years of land change in Georgia: forest degradation, land-use patterns, and drivers

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In this talk, we present results from a study, funded by the NASA Land-Cover and Land-Use Change program, of thirty years of environmental change in the country of Georgia. The country, a former Soviet Union Republic, has experienced more political, economic and social change in the last 30 years than most countries. But the environmental implications of these extreme events remain largely unknown – the region is understudied, no national forest inventory has been completed in 20 years, and previous research in the area conducted by the authors were not successful. The latter statement is because of forest degradation. After the collapse of the Soviet Union, much of the forestry infrastructure broke down and people resorted to chopping down individual trees. The result was in many parts of the country a reduction in forest biomass but not to the point of a change in land cover. This type of forest degradation, which was either gradual over decades or abrupt, could not be readily identified using the methods and data at our disposal at the time. In the recent study, we had full access to the Landsat archive in combination with computing power. By using monitoring methods that are based on time series analysis, we were able to capture and identify the gradual processes driven by small scale activities that are so characteristic of the post-Soviet Georgian landscape. We developed an approach ("CCDC-SMA") that combines time series analysis and spectral mixture analysis running on Google Earth Engine for monitoring abrupt and gradual forest degradation. By using this approach, we found that forest degradation was significantly larger than the area estimate of deforestation; 3,541 ± 556 km^2 (11% of the forest area in 1987) compared to 158 ± 98 km^2 from 1987 to 2020. The prevailing narrative is that legal and illegal cutting of trees for fuelwood is primarily responsible for this process. Yet, since independence from the Soviet Union in 1991, the country has undergone rapid socioeconomic and institutional changes which have not been explored as drivers of forest change. To further our understanding of the underlying causes, we combined forest disturbance estimates, Georgian statistical data, and historical institutional change data to examine socioeconomic drivers of forest degradation. We found that higher winter temperature and drought were associated with higher degradation at the regional scale, while major institutional changes and drought were associated with higher forest degradation at the national level. Access to natural gas, the major energy alternative to fuelwood, had no significant association with degradation. Our results challenge the narrative that poverty and a lack of alternative energy infrastructure drive forest degradation and suggest that government policies banning household fuelwood cutting, including the new Forest Code of 2020, may not reduce forest degradation. Given these results, improved data on wood harvesting and more research on the commercial drivers of degradation and their links to economic and political reforms is needed to better inform forest policy in the region, especially given ongoing risks from climate change.

Clear Cut Mapping Using Sentinel-2 and PRISMA Hyperspectral Imagery

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Forest ecosystems are increasingly vulnerable to a multitude of stressors, including droughts, wildfires, human activities, clear-cut and alterations in land use patterns. As such, safeguarding these ecosystems and enhancing their ecological functionalities are paramount imperatives delineated by the European forest and biodiversity strategies. Multispectral remote sensing data provide a means to comprehensively analyse the structure and functioning of forests and can be put into operational use for the continuous monitoring of forest harvests at country level.

Hyperspectral remote sensing enhances the optical capability by expanding the number and preciseness of reflectance bands available in the VNIR and SWIR regions and providing the potential to detect biophysical processes of soil and vegetation such as wood degradation, and soil moisture. However, the reliability of these data is contingent upon various factors, such as scale, spectral and geometrical resolutions.

This study aims to assess the added-value provided by hyperspectral products from the Italian Space Agency (ASI) PRISMA mission in characterizing active clear-cut areas taking operational state-of-the art multispectral data (Copernicus Sentinel-2) as a reference. Given the growing importance of monitoring such areas using state-of-the-art approaches, the hyperspectral images ready accessibility significantly enhances the ability to observe and understand the evolution of forest systems and provides an advanced perspective for the management of the latter.

Three study sites were located in deciduous forests in Tuscany (Italy). Administrative ground-truth data about past harvest operations in forests were checked by photo interpretation and spatially located in each study site.

Supervised machine learning models, trained and validated on ground-truth data were deployed on Sentinel-2 and ASI PRISMA products. Accuracy and precision of the two models in the identification of harvest areas was evaluated by comparing their RMSE and other measures of uncertainty.

Results are discussed in the framework of the launch of the next generation of hyperspectral satellites (CHIME, PRISMA 2G, IRIDE) and the provision of harvest volume data in the commercial, political and forest governance at EU level.

Continental-scale mapping of supratidal and coastal floodplain forests of Australia

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Australia's coastal wetlands include a diversity of vegetation structures and compositions across intertidal and supratidal elevations. While there have been significant recent advances in continental-wide information on mangrove and saltmarsh, neighbouring supratidal forests represent a significant missing link in knowledge of the distribution of coastal ecosystems in Australia. Without the ability to classify supratidal forests using remotely sensed imagery, it is currently not possible to identify where this ecosystem exists across Australia or to track changes over time, including increases in extent from restoration projects.

Here, we present the first continental-scale mapping of supratidal and coastal floodplain forests of Australia. This approach is based on emerging conceptual understanding of characteristics and biophysical drives along the multiple coastal settings around the country. We consider supratidal and coastal floodplain forests broadly defined by their a) position within the coastal landscape and b) vegetation structure. We utilise Earth observation data, primarily from the Landsat archive, as well as globally available products accessed and analysed using Geoscience Australia's Digital Earth Australia (DEA) platform. For identifying position in the landscape, we leverage existing products such globally available elevation data, Water Observations from Space (WOfS; Mueller et al., 2016) and the Intertidal Extent Model (ITEM; Sagar et al., 2017), together with information on highest astronomical tides and storm surge across the continent. For vegetation structure, we leverage existing products such as DEA Mangroves (Lymburner et al., 2020), Australian Saltmarshes (Murray et al., in prep), Tidal mudlfats (Murray et al., 2019), and Woody Cover Fraction (Liao et al., 2020). The output products of this mapping approach provide information on the confidence associated with the presence of supratidal and coastal floodplain forests in the landscape.

We present first estimates of supratidal and coastal floodplain forest extent across Australia. Field measurements and associated validation data demonstrate strong agreement with the supratidal and coastal floodplain confidence layer. These mapping products will benefit a range of end-users, including Federal and State/Territory Government portfolios responsible for monitoring and managing coastal wetland resources across Australia. In addition, this information will assist regulators and project developers of blue carbon projects to better understand coastal wetland extent and restoration opportunities via new Blue Carbon methods under Australia's Emissions Reduction Fund.

ForestInsights: Mapping New Zealand's forests through deep learning and data-centric AI

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The effective management of New Zealand’s existing and future forests relies on detailed information of their extent, location, and characteristics. However, fine-level information describing planted forest location and extent is currently lacking at a national level and is often only available for large scale plantation estates, overlooking the significant contribution of woodlots and shelterbelts, and the potential for large-scale afforestation by small growers.

Leveraging powerful advancements in AI technology and freely available imagery and LiDAR data that is routinely captured by regional councils, Scion’s ForestInsights project aims to establish a comprehensive depiction of the whole of New Zealand’s planted forest estate.

A high-resolution map of New Zealand’s radiata pine forests and woodlots was produced using a deep learning AI model developed for use with RGB aerial imagery. The model was trained on a large dataset of hand-labelled aerial imagery ranging from 15 – 30 cm spatial resolution with a wide variety of visual characteristics, enabling the model to be highly generalisable across imagery captured under a broad range of conditions. Once mapped, forests can be characterised using airborne LiDAR data, from which important metrics such as tree height, stocking, volume, and biodiversity (e.g., forest structure) can be accurately derived.

Work is currently underway to incorporate other planted forest species and to extend the approach across the whole of New Zealand as the national LiDAR acquisition programme progresses. The establishment of this baseline represents foundational work that will enables us to better describe where our forests are, what they contain in terms of timber, and drive greater understanding of this critical resource at a national scale.

Global estimations of forest biomass: a review study

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Accurate estimates of forest biomass (e.g., aboveground biomass - AGB) and carbon stocks are becoming more important due to the key role of forests in the global carbon cycle and climate change. Mostly, parties of the Climate Convention may be obliged to report annual estimates of carbon pool changes. Two main methods: design-based and model-based inference approaches are often used. However, these methods are characterised by several challenges such as lack of field data, coarse resolution or partial-coverage of remote sensing data, and incomplete comprehension of certain features of methods of inference. The resulting effects are large uncertainties in AGB estimates. Further, most studies tend to report conflicting findings, highlighting the various sources of uncertainty inherent in AGB surveys.

The purpose of this study was to assess methodologies used for AGB estimation and mapping from local to global scales. To this end, 80 studies conducted between 1992 and 2022 were systematically reviewed. As a basis for the review, we propose ideal methodological standards for different sections of a comprehensive AGB survey. It should be noted that fulfilling all parts of the standards is probably impossible in practice, and thus should mainly be seen as a tool for identifying which parts of AGB surveys tend to be more problematic than others. The selected standards are distinct between surveys adopting design-based inference (including model-assisted estimation) and those adopting modelbased inference. The standards comprise a set of criteria where a number of indicators describing quality and reliability were established. Examples of these criteria include properties of the remotely sensed data used, properties of the field data used, the statistical procedures applied, and the methods adopted for quality assurance and quality control. For each criterion, we grade the workflow from 1 to 5 ("poor", "fair", "good", "excellent", and "outstanding", respectively), and summarise the results across all studies.

Preliminary results show an increasing quality of forest biomass assessments during the last three decades. Many of these studies work on a small scale and obtain fair results and overall “good” to “excellent” quality in our review. The use of model-based inference approaches is increasing over time due to the recent advancements in remote sensing technologies. However, large-scale AGB assessments focused on model-based inference tend to be rated lower due to several issues, for instance, a lack of understanding of model prediction unbiasedness and statistical control of domain-specific model performance. Studies adopting model-assisted inference obtained better results compared to model-based due to the complete control of local errors in AGB maps using probability field samples.

We do not reveal our grading of individual studies but use the overall results for identifying what parts of surveys tend to be more problematic than others, and discussing what developments would be relevant from the point of view of enhancing the overall quality of large-area AGB surveys.

Mapping the risk for wind and snow damage using NFI field plots and auxiliary remote sensing and weather data

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There is an urgent need to adapt forest management to make boreal forests less susceptible to climate change impacts. Storm and snow are today one of the main reasons for forest damages in Sweden; based on statistic of Swedish national forest inventory (NFI) over 2,2 % of productive forest land has been affected by wind and snow damages in last 5 years. There is a fear that climate change will make forests more sensitive to storm and snow damage, especially if forest management is not adapted.

The purpose of this study was to create the first general risk model for wind and snow damage in Sweden to support decision making in forest management. This was done by testing the usability of existing remote sensing based forest data together with stand neighborhood and weather variables to predict damage risk. In the modelling, we used 2 046 damaged and 51 234 not damaged plots monitored between 2003-2022 by the Swedish NFI over the whole Sweden, including plots with a mean tree height > 5 m. Tested prediction variables included airborne laser (ALS) based structural forest and terrain information, ALS- and satellite-image based vegetation type and tree species information, stand neighborhood information, soil information and weather variables, all together over 110 variables. ALS products comes from two national campaigns (2009-2019 and 2018-2023) with point densities 0.5-1 and 1-2 points/m2, vegetation type map from 2018 and tree species maps from 2021. The mean values of weather variables were extrapolated from the 2007-2023 daily weather database. The grid-cell size of map products were 2m, 10m and 12,5m and 2,5km depending on the product. Different prediction models were tested including Generalized Linear Models (GLM) and Additive Models (GAM) and neural networks. Models were created separately for two geographical areas: the middle-south and the north, based on the snow depth data and Swedish NFI regions.

Based on our preliminary results the most important variables in the models are: tree height, snow depth, dominant species, temperature, maximum wind speed, most common wind direction, distance to closest clearcut and soil depth. The two geographic areas have differences regarding the importance of some variables. For example, in the middle-south the distance to clear cuts and wind direction have more importance than in the north, when soil depth and days with temperatures above zero have more importance in the north. Our study shows that we can successfully predict risk for wind and snow damage using combination of NFI data together with wall-to-wall remote sensing and weather data in Sweden. The results of the study will be used to create the first wall-to-wall risk maps for wind- and snow damage over the whole Sweden, which enable evaluation of abundance and distributions of the risk in stand to regional and national level. By locating potential areas with high risk for damage forest owners and other decision makers can more easily adapt their forest management for climate impacts.

Developing an individual tree model to quantify crown damage of Coastal Grey Box (Eucalyptus bosistoana F. Muell.) using UAV in New Zealand

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In recent years, Eucalyptus plantations have been expanding to produce a naturally durable timber in drylands of New Zealand. These plantations are highly vulnerable to insect herbivory, leading to severe crown damage. For effective pest management, accurate and timely detection, quantification, and monitoring of crown damage at the individual tree level are crucial. However, current assessment methods rely on subjective ground-based visual evaluations, which are labour-intensive, time-consuming, costly, and impractical in inaccessible areas. This study aimed to develop a species-specific model for precise estimation of Eucalyptus crown damage using remote sensing techniques. The study was conducted in *Eucalyptus bosistoana* F. Muell. breeding trials in Sefton, New Zealand. We purposively selected 170 individual trees with varying degrees of crown damage (ranging from 0 to 100% at 5% intervals). For each tree, we collected four leaf samples from four vertical heights of a live crown, each height facing different orientations. We photographed the leaf samples and assessed tree-level quantitative crown damage index (CDI) using an image processing program (ImageJ). Additionally, we captured unpiloted aerial vehicle (UAV) LiDAR and RGB imagery using DJI Matrice 300. Spectral, structural, and textural metrics related to greenness, crown width, crown length and crown density of individual trees were extracted and used as predictor variables, while the CDI served as the response variable. We evaluate three models - Partial Least Square Regression, Random Forest, and Support Vector Regression, to quantify crown damage. Based on the preliminary results, we anticipate that this study will provide a best fit model to estimate individual tree-level crown damage with higher accuracies of R^2, RMSE and MAE. This alternative method could offer an accurate, reliable, objective, and unbiased approach for quantifying eucalyptus crown damage using UAV remote sensing, thereby surpassing the limitations of ground-based assessments. The developed model will facilitate the detection, monitoring, and management of eucalyptus forest health for growers and planners in New Zealand and beyond.

Keywords: Crown damage, LiDAR, Machine learning, RGB image, UAV

Detecting and measuring urban tree loss at the property scale with remote sensing data

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Introduction:

Urban trees provide a multitude of environmental and amenity benefits for city occupants yet face the constant risk of removal due to urban pressures and the preferences of private landowners. Understanding the patterns and drivers of tree loss on private land is critical for the effective management of urban forests. Although city-scale assessments of urban forest canopy cover are common, the accurate identification of urban tree loss at the property scale remains challenging. Evaluating change at the property scale is of particular importance given the localised benefits of urban trees and the scale at which tree removal decisions are made.

Aim / Methods:

The objective of this research is to detect and quantify the city-wide loss of tree canopy (minimum 3m height and $3m^2$ area) at the scale of individual properties using publicly available remote sensing data. The study area is the city of Christchurch, New Zealand, with the study focussed on tree loss that occurred between 2016 and 2020. Due to the variable quality and alignment of available remote sensing data, a variety of methods have been utilised to create accurate canopy maps for these two dates. For 2016, a semantic segmentation deep learning model (DeepLabv3plus) was trained using high resolution aerial imagery (RGB, 7.5 cm) and used to predict city wide canopy cover. Although similar aerial imagery was available for 2020, it was poorly aligned with the 2016 imagery, which precluded its use for accurate change detection. A 2020 canopy map was therefore prepared utilising classified LiDAR point cloud data (25 pts / m^2), which was better aligned for comparison with the 2016 canopy map to identify tree loss over time. Tree loss predictions were ground-truthed using a visual comparison of aerial imagery for several test areas throughout the city (45 image tiles of 57.6 m^2 each), with the tree loss quantified by canopy area and volume for each property within the study area.

Results / Conclusion:

At the date of writing, the deep learning model has produced an accurate canopy map for 2016 (mean IoU >90%; overall accuracy >97%). Preliminary comparisons with the LiDAR based canopy map for 2020 have produced promising results for property scale identification of tree loss (mean IoU >78%, overall accuracy >98), with further refinements currently being explored. This research provides a geospatial method for evaluating fine-scale city-wide tree dynamics in urban areas using a variety of remote sensing data. This creates the opportunity for detailed evaluation of the drivers of urban tree loss on private properties to enable better management of existing urban forests.

An early national assessment of the 2024 wildfire season in Canada

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Introduction/Aim:
Wildfires have always been present over Canada's forested landscapes [1,2], and an increased in fire activity is expected to be a consequence of the changing climate [3]. The lengthening of fire seasons over the last decades [1,4], and the increasing frequency of fire-prone weather conditions [4–6] are expected to continue producing conditions for intense fire seasons in Canada.

Rapid detection of wildfires is essential to support the allocation of firefighting resources and ensure the safety of communities [7]. Existing approaches to map active fires allow the rapid first order delineation of wildfires to inform emergency response activities. The trade-off is that unburned areas can be included in those preliminary maps. Using medium spatial resolution (10 – 100 m) optical sensors for the initial detection of fire is known to be limited by smoke, cloud, and haze. However, a within-year time series of images can mitigate the impact of atmospheric interference and provide multiple temporal observations to refine and improve mapping of burned areas.

The aim of this presentation is to show the preliminary burn areas of the 2024 fire season in Canada at a 10-m spatial resolution. Additional insights on land cover types impacted by wildfires and the treed aboveground biomass consequences will be provided.

Methods:
Our analysis will be conducted on the forest dominated ecozones of Canada (650 Mha) that largely consist of treed areas (362 Mha) [8].

Burned areas will be identified by leveraging the four-satellite virtual constellation formed by Sentinel-2A and -2B with Landsat-8 and -9 via the cloud computing environment of Google Earth Engine and the Tracking Intra- and Inter-year Change algorithm [9]. This algorithm enables the identification of stand-replacing disturbances based on a time series of images. TIIC builds an expectation time series of the spectral signature of a pixel from one or more past years, and compares new images to that expectation as obtained. Because the fire season may well be continuing into September 2024, we expect to produce maps showing fire activity up to the conference date.

Results:
This methodology was established for the 2019 growing season [9], and used to analyse the record-breaking 2023 fire season in Canada [10]. We found that 12.74 Mha of land was burned in 2023 across the Canadian forested ecozones — a total almost 8 times greater than the long-term annual average burned area of 1.6 Mha [11,12]. Treed vegetation comprised 75% of the burned area, which led to the loss of approximately 0.65 Pg of aboveground treed biomass [10].

Conclusion:
The spatial detail captured by TIIC offers a rapid means to create annual burned area estimates that can accurately map burned areas and associated impacts at a fine resolution during a fire season. This approach can serve as a complement to active fire mapping methods used for emergency planning. Together, TIIC and existing delineation approaches can reduce the latency of accurate, fine-scale mapping, while serving some of the on-going needs of the fire management and planning communities.

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Tower-based radar observations of sub-daily water dynamics in boreal forests

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Radar remote sensing observations are predominantly affected by the concentration and spatial distribution of water in natural scenes. This motivates the utilization of high-resolution spaceborne radar observations for monitoring the water status of vegetation and the impacts of climate change on forests globally. While current satellite-based synthetic aperture radar observations are limited to temporal resolutions of days, tower-based radar observations of forests are capable of capturing detailed sub-daily physiological responses to variations in soil water availability and meteorological conditions. Such experiments demonstrate the scientific value of prospective sub-daily space-borne observations in the future.

The BorealScat tower-based radar experiment conducted in southern Sweden from 2017 to 2021 has captured various ecophysiological phenomena in a boreo-nemoral forest, including water stress and degradation induced by spruce bark beetles (*Ips typographus*). To gain a deeper insight into the sub-daily impacts of forest water dynamics on radar observations, the BorealScat-2 tower-based radar experiment was initiated in a boreal forest, located in northern Sweden in 2022. Along with *in-situ* sensors characterizing the water status on the tree level and an eddy-covariance flux tower, this initiative aims to compile a comprehensive and open dataset. The goal is to enhance our understanding and modelling of the relationship between traditional ground-based forest information, eddy-covariance flux measurements and radar remote sensing observables.

The data gathered by BorealScat-2 stands out as the most radiometrically precise high-resolution time series ever recorded in forest environments, resolving the subtle water content-induced signatures in radar measurements. Preliminary findings from the 2022 growing season, highlight the detectability of a diurnal radar signature across all conventional radar remote sensing bands (i.e. C-, L- and P-band). Moreover, metrics akin to tree water deficit, as measured by high-resolution point dendrometers, can be derived from interferometric radar observations. The fine temporal resolution of the data also unveils distinct signatures corresponding to intercepted precipitation in time series measurements. These findings underscore the need for sub-daily observations from space-borne satellites to monitor vegetation water status.

Drone based SAR imaging of forest

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Introduction/Aim: The synthetic aperture radar (SAR) has long been used from satellites for forest monitoring at global level. The boreal forests in Sweden are well described wall-to-wall from airborne laser scanning and airborne photography, causing SAR as sensor type to provide only limited added value, due to the lower resolution compared to other sensors, despite its all-weather acquisition capabilities. Yet, by accounting for various interfering effects that currently degrade the useful information in SAR images, it can be extremely valuable for both vegetation mapping and belowground mapping (e.g., soil conditions). In the current work, we present the configuration of a drone-based SAR experiment that allows us to image the forest in very high spatial resolution.

Methods: The drone-borne multi-band interferometric SAR system acquires data in the P-, Land C-bands. Using a helical flight trajectory enables an accurate tomographic reconstruction in 3D, both above and partly below ground. The spatial resolution is ~20 cm in the P-band, ~6 cm in the L-band, and ~2 cm in the C-band. The drone acquisitions cover forest from mineral soil, a peatland area, and a gravel road, hence providing different soil conditions. The various soil moisture conditions are quantified in-situ using soil moisture sensors and simulations of the ground water table. The trees were scanned using terrestrial, mobile, and airborne laser scanning during 2023 and 2024, and sap flow sensors will be installed during the spring 2024 to enable modelling of the evapotranspiration in the trees. Additionally, ground-penetrating radar will be used for ground measurements in 2024. The reconstruction of both singletree properties above ground as well as soil characteristics are currently analysed.

Results: We expect the accurate height and density information provided from the SAR acquisitions to enable accurate estimates of the tree biomass and tree shape. Furthermore, we explore the penetration into the soil by putting the tomographic focus below ground, which would allow us to derive information potentially related to the trees' root structures.

Conclusion: Utilizing the newly developed drone-based SAR system facilitates in-depth exploration of complex forest structures. Through this research endeavour, our objectives encompass enhancing comprehension of evapotranspiration in trees, reconstructing forest characteristics, evaluating the influence of weather factors, and investigating SAR's reflectivity and penetration capability through the canopy and soil in a boreal forest setting.

Comparison of Satellite- and Drone-based SAR Imaging of Forest

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Introduction/Aim:
Synthetic Aperture Radar (SAR) has been a longstanding tool for global forest monitoring when used from satellites. In Sweden, boreal forests are comprehensively characterized using airborne laser scanning and photography. As a result, SAR's contribution is somewhat limited due to its lower resolution compared to other sensors, despite its ability to acquire data in all weather conditions. However, by addressing various interfering factors that currently diminish the quality of SAR images, it can prove highly beneficial for vegetation mapping. In the current work, we compare SAR images acquired from satellites with those acquired from a drone, and we raise the discussion on how to enable useful applications based on satellite based SAR.

Methods:
Satellite images were acquired at X- (ICEYE, COSMO-SkyMed, TanDEM-X), C- (Sentinel-1) and L-band (SAOCOM), respectively. The drone-borne multi-band SAR system acquired data in the P-, L- and C-bands. A helical flight trajectory enabled an accurate tomographic reconstruction in 3D as well as the generation of backscatter images. The spatial resolution was ~20 cm in the P-band, ~6 cm in the L-band, and ~2 cm in the C-band, while the resolution of the satellite images ranged from a few meters to about 20 meter. A forest area of about 0.6 ha were measured *in-situ* using a caliper and positioned using PosTex system and a GNSS receiver, and the biomass was estimated from national functions.

The backscatter across the different sensors will be compared and their correlation to AGB, land type, as well as the positional accuracy will be analysed. The positioning will be quantified by using two corner reflectors located within the forest area.

Results:
We expect the interferometric and tomographic information to provide useful information about the forest, to estimate biomass etc., while the backscatter at the shorter wavelengths are commonly greatly affected by speckle noise which in combination with the scattering in the forest make it less useful for biomass estimation. It is also important to understand the backscatter levels of the drone-based acquisitions in relation to satellite-based, to enable future up scaling based on the drone.

Conclusion:
Radar has an important role in mapping forests, but the usefulness is highly dependent on the configuration of the platform and radar. To fully enable the mapping at scale provided through satellite based SARs, the spatial resolution needs to be improved and the SARs need to provide more information than backscatter at a single polarization. This can, e.g., be bistatic SAR acquisitions and fully polarimetric data.

Remote Sensing-based Two-Phase Forest Inventory using High-resolution Laser Scanning

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Introduction/Aim:
Remote sensing (RS) has been extensively used within various statistical inference frameworks for estimating forest variables. This study presents an entirely RS-based forest inventory approach using terrestrial laser scanning (TLS) data and samples of very high resolution (VHR) airborne laser scanning (ALS) data within a hybrid-inference framework for estimating the total stem volume of a test site. The variance of the design-phase dominated the total uncertainty and two methods were tested for estimating the design-phase variance: A) Increasing the sample variance of the ALS strips by splitting them into smaller grid cells at various regular spatial intervals, and B) using the established Matérn variance estimator based on splitting the strips into square cells of equal dimensions.

Methods:
The test-site is located in mid-Sweden covering 5km^2. The VHR ALS data with an average point density of 593 points/m^2 was acquired in 4 systematic strips of 11km length and 0.1km width (design-phase). Thirty-two points were distributed randomly within the 4 ALS strips, where TLS scans were done using a single-scan mode to provide diameter estimates of trees. An individual tree crown (ITC) segmentation algorithm was implemented for detecting trees in the laser data. ALS metrics were derived for each ITC segment. The segmented TLS and ALS ITCs were linked based on diameter estimates, transformed geolocations, and proximal tree top distances within 10m search radius. The stem volume of TLS trees (VOL_{TLS}) were estimated using allometric functions. A model for VOL_{TLS} as a function of ALS metrics was developed, $VOL_{TLS}=\beta_0+\beta_1X_1+\ldots+\beta_pX_p$, where $[\beta_0,\beta_p]$ are the model coefficients for p ALS metrics selected as explanatory variables (model-phase). Hence, the tree-level stem volume could be estimated for all ALS ITCs, which were then used in a ratio-estimator to predict the stem volume for the entire test-site based on the 4 ALS strips. The variance of the design-phase with method 'A' was estimated by splitting the strips into grid cells at equal intervals and implementing a random sampling variance estimator for systematic subset of the grid cells. The theoretical derivation of this approach remains to be developed, whereas, for method 'B', the strips were divided into square cells of equal dimensions and further split into equal halves horizontally and vertically followed by implementing the Matérn cross-variance estimator.

Results:
The total stem volume per hectare (ha) was estimated as 123.3m^{3}ha^{-1} for the test-site. The variance of the model-phase for hybrid inference contributed less than 1%, while the variance from the design-phase contributed around 99% of the total variance. The standard errors ($\widehat{se}$) from the two methods were: (A) 6.33m^{3}ha^{-1} (5.1%) and (B) 4.35m^{3}ha^{-1} (3.5%).

Conclusion:
This study proposes that an entirely RS-based forest inventory can be conducted using VHR laser data using hybrid inference. Alongside, this study compared two methods for estimating the design-phase variance, where the Matérn estimator (method 'B') indicated the lower variance. The total uncertainty appeared relatively low compared to model based wall-to-wall approaches and the sample based design phase is cost efficient and allows the inventory to be repeated more frequently than wall-to-wall inventories.

Towards a Generative approach to Estimating Soil Carbon Distributions in Subtropical Forested Environments

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Land use conversion is profoundly changing above- and belowground forest carbon cycling in the Hawaiian Islands. Contemporary drivers of forest change in Hawai‘i contrast with historical and global patterns. For example, the abandonment of agricultural lands has facilitated the encroachment of woody species into areas previously void of forests. Tropical and subtropical forests, like those in Hawai‘i, sequester a significant amount of carbon belowground in soils. To elucidate and spatially cluster the complex, interacting drivers influencing soil carbon dynamics across Hawai‘i’s diverse climates and landscapes, we analyzed Forest Inventory and Analysis (USFS-FIA) and other Hawai‘i-based forest soil carbon data, climate and geology, and landsat and GEDI data in a generative framework aimed at delineating regional distributions of soil carbon. Our approach highlights how land use and land use changes drive soil carbon processes differently across regions. Our findings offer a framework for the expression of multimodality in soil carbon predictions that better reflects the manifestation of soil carbon distributions across landscapes. The ability to include improved region-specific drivers in process-based carbon cycling models will enhance our ability to manage and conserve Hawai‘i’s unique tropical forest ecosystems in the face of ongoing environmental change.

Mapping changes in forest landscapes in the conditions of forest disturbances and afforestation of abandoned agricultural land in Northeastern Europe during recent history

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Intensification of forestry and abandonment of agriculture are the processes that modify patterns in forested landscapes. Forested areas are under anthropogenic pressures of creating (temporary) openings mostly by logging, but in places also by natural agents. Simultaneous occurs the expansion of forest into formerly non-forested land that has previously been mostly in agricultural use. Detection and proper location of both types of edges: newly created edges and expanding edges is a major challenge to forest scientists and forest mappers.

Such human caused changes of forests can be expected to vary among regions with different landscape properties and land use history, both along the north-south and east-west gradients. We estimated the occurrence and rate of forest changes, both gap-area dynamics and forest expansion events in Northeastern Europe the areas of Finland, the three Baltic states, Belarus and Russia, using Landsat satellite images

Images from February and March were used, when the ground was covered with snow. Bright snow amplifies the contrast of non-forested background with dark tree crowns and their shadows, favoring to follow dynamics of tree crown coverage with more success than it is conceivable in summer seasons. We hypothesized that both the latitudinal and longitudinal gradients will be reflected in gap size distributions, grouping of gaps in forested landscapes and temporal trends in emergence of new gaps.

We found, indeed, that forest gaps in western more intensively managed regions are smaller than in the east, where forest areas have been less intensively used for centuries. However, there are also region-specific dynamics of gap size, which can have multiple reasons, unrelated to the landscape nature.

332

Deep learning and machine learning for forest management at Timberlands Ltd., New Zealand: Detecting young trees and satellite change detection

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Remote sensing offers cost-efficient and timely solutions for forestry management at various scales. This presentation will demonstrate the applications of remote sensing technologies in forest management at Timberlands Ltd., New Zealand, focusing on the integration of deep learning and UAV (unmanned aerial vehicle) technologies for identifying and mapping young individual trees. These applications are crucial for assessing the survival rate of stands and evaluating the health and vigour of seedlings. Additionally, the presentation will highlight the use of satellite data (Sentinel-2) and machine learning algorithms to detect forest changes, including the identification of harvested areas. Furthermore, we will demonstrate how the results from remote sensing analysis can be visualized in real-time through interactive dashboards, providing timely and valuable information. Through these examples, we aim to illustrate the potential of advanced remote sensing technologies in enhancing forest management practices.

Hyperspectral Remote Sensing for Monitoring Radiata Pine Health: Nutrient Status and Disease Detection

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Radiata pine (Pinus radiata D. Don) is a crucially planted species that requires vigilant monitoring to ensure optimal growth and mitigate pathogenic risks. Nutrient deficiencies and over-fertilization pose significant growth limitations, highlighting the importance of continuous monitoring. Specifically, the assessment of Nitrogen (N) levels, traditionally monitored through the link with chlorophyll *a+b* (C_{a+b}) content, emerges as pivotal for determining overall plant health. Moreover, diseases like Dothistroma needle blight (DNB), caused by Dothistroma septosporum and D. pini, induce chlorophyll concentration decreases via the synthesis of the dothistromin toxin, further emphasizing monitoring imperatives.

Remote sensing techniques employing hyperspectral imagery offer promising avenues for quantifying key biochemical indicators such as C_{a+b}, facilitating leaf Nitrogen quantification, and early DNB infection detection on a large scale. However, the structural complexity of pine crowns, compounded by clumped leaves/needles and background effects, presents challenges for accurately quantifying physiological parameters.

This study investigates the impact of scene components and segmentation strategies on chlorophyll concentration quantification through Radiative Transfer Models (RTM) inversion techniques. Results reveal varying accuracies between pure-vegetation pixels and full-crown spectra, with PRO4SAIL2 model exhibiting superior performance than other standard RT models in predicting needle C_{a+b} concentration. Furthermore, the study explores utilizing plant traits derived from remote sensing data to enhance DNB detection accuracy. Models incorporating pure vegetation traits outperform those reliant solely on hyperspectral indices, with early-stage disease detection benefiting from parameters describing photosynthesis and chlorophyll degradation. Conversely, severe disease stages are best characterized by traits reflecting extreme reductions in carotenoid content and foliage loss.

The predictions of needle C_{a+b} were more accurate from PRO4SAIL2 than from PRO4SAIL, using both full-crown (R^2=0.82; 3.35 µg/cm^2 vs R^2=0.51; 4.88 µg/cm^2) and pure-tree-crown spectra (R^2=0.69; 4.03 µg/cm^2 vs R^2=0.7; 4.17 µg/cm^2). Interestingly, for PRO4SAIL the accuracy of predictions was higher for pure-vegetation pixels than for full-crown spectra, while the reverse was true for PRO4SAIL2, with its highest accuracy being for predictions using full-crown data (RMSE = 3.35 µg/cm^2).

For disease detection, models using plant traits obtained from pure vegetation as inputs showed an accuracy of R2 of 0.85, compared with R^2 = 0.52 when using only narrow-band hyperspectral indices. Early stages of the disease were most readily distinguished from asymptomatic trees using variables that predominantly describe changes in photosynthesis (Photochemical Reflectance Index), chlorophyll degradation (Normalized Phaeophytinization Index), and chlorophyll content. In contrast, the more severe impacts of the disease were most well characterized by traits associated with an extreme reduction in carotenoid content and loss of foliage (through LAI and LIDFa).

Overall, these findings underscore the potential of remote sensing for monitoring nutrient status and DNB in radiata pine plantations. By integrating leaf trait estimation with disease detection, forest managers can access valuable insights into tree health, optimize fertilization practices, and implement targeted disease control measures for enhanced forest productivity and sustainability.

Remotely sensed and spatially explicit environmental variable selection to model soil Pyrogenic Carbon (PyC) fraction of soil Total Organic Carbon (TOC) in the Amazonia-Cerrado transition

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Pyrogenic carbon (PyC), a fraction of Total Soil Organic Carbon (TOC) formed through the incomplete combustion of biomass, plays a crucial role in the soil of the Amazon rainforest (Koele et al. 2017). PyC is stable due to its chemical structure and it persists in the soils for millenia (Vedovato et al., 2023), thus acting as a carbon reservoir, enhancing fertility, carbon sequestration capacity (Ziviani et al., 2022). Moreover, PyC increases the Amazon forest resistance to extreme drought (Vedovato et al. 2023) and affects species composition (Oliveira et al. 2020). PyC stock in Amazon forest soils is estimated at 1.1 Pg up to 0.3 m and 2.8 Pg up to 1 m depth (Koele et al. 2017).
PyC in the Amazonian soils is caused by ancient fires (Feldpausch et al. 2022), and to a lesser extent is deposited from soot transportation of distant fires (Silva et al. 2023; Silva et al. 2024). At the landscape scale, PyC is influenced by the mean annual temperature, exposure to oxygen, distance to fragment´s edge (Silva et al. 2023), type of vegetation, soil and terrain drainage (Oliveira et al. 2022; Carvalho et al. 2018), amongst other factors.
Global efforts for mapping the spatial distribution of PyC in the soils are highly uncertain due to the lack of detailed field data with global distribution and, more importantly, due to the high spatial variability in the PyC distribution (Koele et al, de Oliveira et al. 2022), This work, thus, aims to explore the selection of remotely sensed and spatially explicit variables representative of PyC in the southern Amazonia-Cerrado transition, expected to contribute with large scale PyC mapping.
First, 36 variables affecting PyC distribution in the Amazonian soils were compiled from seven scientific articles, published from 2015 to 2024. Then, a spatial explicit database was compiled with 19 bioclimatic variables, 10 soil structure and chemistry layers, 3 topographic features, vegetation type, distance to fragment´s edge, distance to recent fires and LiDAR biomass. A Recursive Feature Elimination (RFE) algorithm, with 10 repetitions, and trained with nine areas reporting the PyC to TOC fraction obtained from Oliveira et al. (2022), revealed that the lowest RMSE (0.01117$\pm$0.005404) was reached with the following eight variables (relative importance in parenthesis): 1) Height Above the Nearest Drainage (1.18e-04); 2) altitude from SRTM (8.58e-05); 3) precipitation of wettest month (6.54e-05); 4) annual mean temperature (3.27e-05); 5) slope (3.24e-05); 6) distance to fragment´s edge (3.17e-05); 7) topsoil pH (2.75e-05) and; 8) topsoil Nitrogen (2.69e-05).
Some variables selected with few training points are in line with the expected PyC to TOC relation for the Amazon, with topographic characteristics, climate and soil pH and N as the main potential predictors. Further analysis with more detailed field data and remotely sensed variables may support spatial modelling of PyC in the Amazonia.

A Continental-Scale Canopy Height Map at 30-m from ICESat-2 and Ancillary Data

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Introduction/Aim: Global canopy height maps from spaceborne lidar offer opportunities for affordable estimation and monitoring of canopy height for a multitude of vegetation applications worldwide. The main objective of this study was to use canopy height information from the ICESat-2 (Ice, Cloud, and land Elevation Satellite-2) datasets along with ancillary Landsat, LANDFIRE and topographic variables to produce a 30-m canopy height product across the contiguous United States.

Methods:
To fill in canopy height values between ICESat-2 tracks, we implemented a canopy height regression model using non-parametric gradient boosted regression trees regression implemented in the XGBoost library. The ICESat-2 canopy height was the dependent variable and the Landsat, LANDFIRE and topographic (slope and aspect) variables, were the independent variables. We selected XGBoost based on its demonstrated better performance over other models, Random Forests (RF) and Neural Networks, in our prior work. We fit the canopy height regression model using 85% of the downloaded data for training with the remaining 15% set aside for testing the performance of the model and control the over-fitting during training. The performance metrics used for assessing model fit included the coefficient of determination (R2), mean bias (Bias), mean absolute error (MAE) and their equivalent percent metrics, percent bias (pBias) and percent MAE (pMAE). We analysed variable importance in the canopy height modeling using SHAP (SHapley Additive exPlanations) values.

Results:
Overall, the fitted model achieved an R2 value of 0.76, a mean bias of 0.1 m, a general over-estimation, and MAE (mean absolute error) of 2.5 m on a validation dataset. Model performance varied across biomes (R2 = 0.49 - 0.73, mean biases = -0.3 to 0.4 m, MAE values= 1.4 to 3.3 m). The best performance was observed in Mangrove sites while the worst was observed in Mediterranean forests. Accuracy assessment with independent airborne lidar canopy heights also varied across biomes with predictions moderately correlated with reference data (R2 = 0.36 -0.58) but lower precision (MAE = 1.4 m – 6.1 m) against various height percentiles including the 50th, 75th, 90th,95th, 98th percentile and the maximum. We observed the best agreement between airborne and ICESat-2 canopy height metrics for corresponding 98th percentile estimates across all biomes.

Conclusion:
In this study our goal was to develop and evaluate a canopy height regression model across different biomes using ICESat-2 heights and multisource ancillary datasets at the extent of continental US. Future efforts will expand the current scale to ultimately produce a global product. The continued accumulation of height data by ICESat-2 will allow a densified sample of canopy heights globally, which will ultimately produce a better product of canopy height with future iterations.

Fine-scale Mapping of Forest Leaf Chlorophyll content using 3D Radiative transfer Modeling

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Introduction/Aim:
Leaf chlorophyll, as the primary pigment involved in plant photosynthesis, is crucial for estimating vegetation productivity and maintaining the balance of carbon flux in terrestrial ecosystems. Therefore, mapping vegetation leaf chlorophyll content (LCC) is of significant practical importance for various agroforest and ecological applications. The integration of remote sensing with radiative transfer models for estimating vegetation biochemical parameters is considered an effective technique. However, the ideal assumption of 1-dimensional radiative transfer models makes it difficult to accurately characterize heterogeneous vegetation environments, resulting in chlorophyll products remaining at coarse resolution scales (300 m -1.15 km), further hindering the development of refined agricultural and forestry management tasks. Although 3-dimensional radiative transfer models based on real scenes offer great potential for finely mapping high-resolution vegetation chlorophyll, the high computational cost of model calculations and the need to calibrate model parameters with field measurements are necessary to simulate more accurate remote sensing signals.
A semi-empirical accelerated 3-dimensional radiative transfer model(3D RTM), named Semi-LESS, is capable of effectively overcoming the aforementioned issues, providing more than 100x accelerations of radiative transfer simulations over heterogeneous canopies. However, the model's inversion of fine-scale vegetation parameters has not been thoroughly investigated due to the covariance of different vegetation biochemical and biophysical parameters and the interference from background.

Methods:
In this study, a semi-empirical 3D RTM, Semi-LESS, was first employed to rapidly simulate multi-band images of UAV under different biochemical parameters combinations. To achieve more realistic simulation of UAV spectral reflectance, airborne LiDAR point clouds were employed to construct detailed 3D forest scenes for model parameterization, with soil heterogeneity also considered by coupling a GSV soil reflectance model. During the inversion process, a 1D residual network was utilized to train the simulated UAV dataset, aiming to account for the influence of various biochemical and structural parameters on LCC inversion. Specifically, the UAV images were aggregated to a 3-meter scale. Subsequently, each pixel's multi-band reflectance, along with corresponding biochemical and structural parameters (LAI), were divided into training (80%), validation (10%), and testing (10%) datasets for training and testing the residual network. To assess the robustness of the model, ground-measured chlorophyll content was also utilized to evaluate the residual network's capability in chlorophyll inversion. The flowchart of the research is presented in Fig.1.

Results:
Our results show a coefficient of determination(R2) of 0.92 and an RMSE of 2.87ug/cm^2 for leaf chlorophyll inversion in 10% of the simulated dataset's testing samples by the residual network. The corresponding values for the ground-measured samples are R2 =0.26, RMSE=8.76 ug/cm^2, respectively.

Conclusion:
Our results demonstrate the capability of Semi-LESS coupled with deep learning to quickly achieve fine-scale inversion of LCC without the need for field-measured data calibration. Our approach also

holds potential for rapidly achieving fine-scale inversion of other vegetation parameters in crop or orchard scenes.

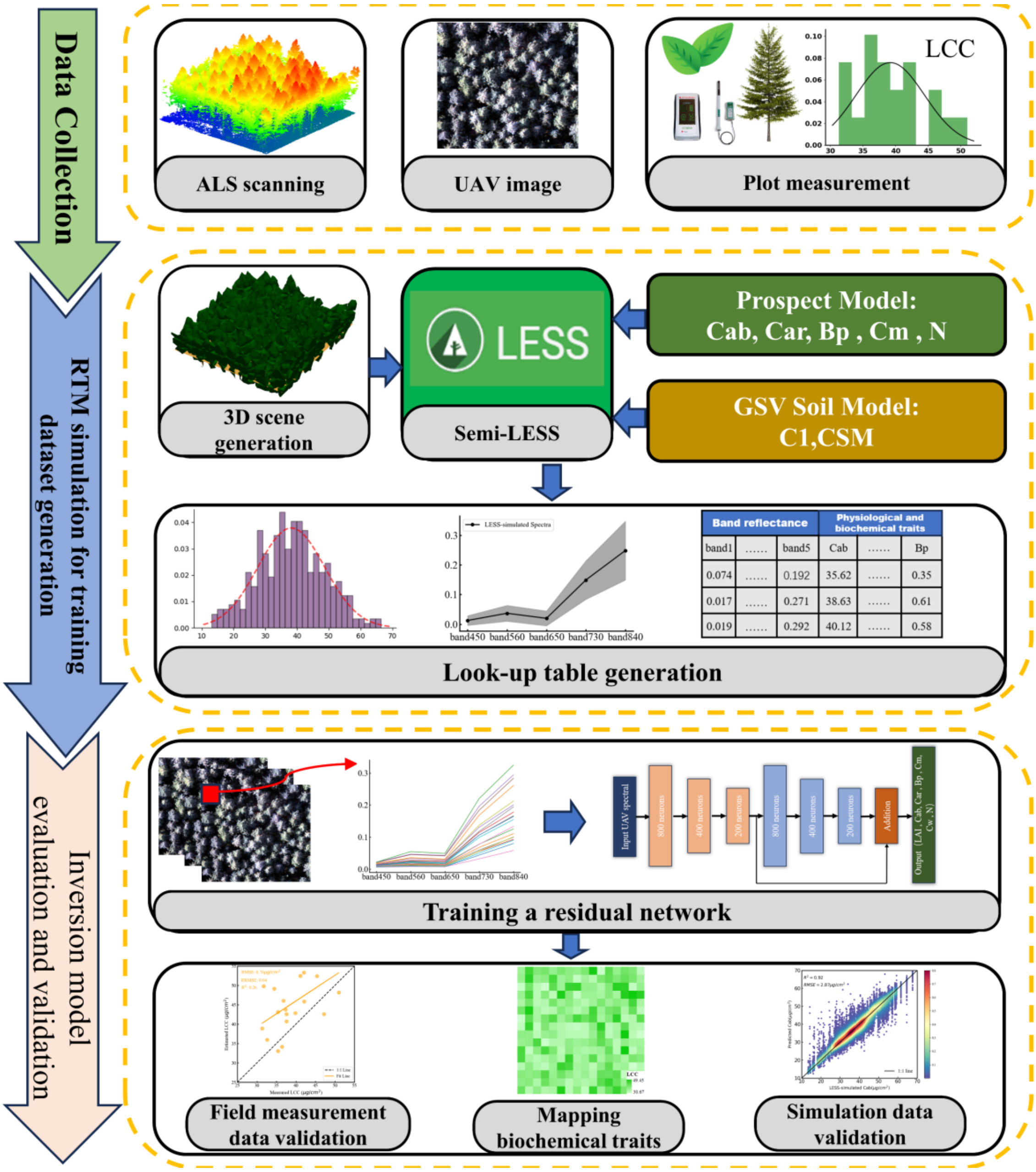

Fig.1. Fine-scale vegetation LCC inversion flowchart diagram

Leveraging Deep Learning and NFI Data for Forest Attribute Mapping from Orthophotos

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In recent years, the Nordic countries have seen the development of detailed forest resource maps, primarily leveraging Airborne Laser Scanning (ALS) data due to its strong correlation with forest structure. However, the considerable cost associated with ALS data restricts the frequency of countrywide updates. In contrast, established national orthophoto collection programs offer extensive archives of highly detailed image data. The advent of machine learning now provides a unique opportunity to exploit these orthophotos for forest attribute prediction. This study explores the potential of using deep learning, informed by data from the Norwegian National Forest Inventory (NFI), to estimate forest attributes based on orthophotos, proposing a method that complements ALS for enhanced forest resource mapping at scale.

In our approach, we employ deep learning techniques to map forest attributes across Norway, utilizing conventional orthophotos obtained nationwide at five-year intervals. This is supported by field data from the Norwegian NFI, with a plot revisiting interval of five years, which inform the training of YOLOv8 image classification models. Specifically, we extracted over 100,000 orthophoto clips from the last decades, corresponding to all NFI plots across Norway, from publicly accessible online services. These clips were annotated with measurements from field data collected subsequent to the orthophoto acquisitions, forming a dataset to model various forest attributes. The models' performance is evaluated against SR16, an ALS-based forest resource map, serving as a benchmark. Initial results indicate that our NFI-informed deep learning models achieve comparable accuracy in classifying specific forest attributes, such as old age, but perform not as good in forest development stages with closed, uniform canopy cover.

Our findings suggest that deep learning models, informed by NFI data and trained on conventional orthophotos, offer a viable supplementary tool for mapping forest resources in specific contexts. This method not only diversifies the available tools but also improves the accessibility and cost-effectiveness of large-scale mapping of forest attributes. Furthermore, the capacity to analyze historical orthophotos with this methodology holds promise for advancing our understanding of detailed forest dynamics on a large scale.

25

SegmentAnyTree: A sensor and platform agnostic deep learning model for tree segmentation using laser scanning data

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This research focuses on advancing individual tree crown (ITC) segmentation in lidar data, developing a sensor- and platform-agnostic deep learning model transferable across a spectrum of airborne (ULS), terrestrial (TLS), and mobile (MLS) laser scanning data. In a field where transferability across different data characteristics has been a longstanding challenge, this research marks a step towards versatile, efficient, and comprehensive 3D forest scene analysis. Central to this study is model performance evaluation based on platform type (ULS vs. MLS) and data density. This involved five distinct scenarios, each integrating different combinations of input training data, including ULS, MLS, and their sparsified versions, to assess the model's adaptability to varying resolutions and efficacy across different canopy layers. The core of the model, inspired by the PointGroup architecture, is a 3D convolutional neural network (CNN) with dedicated prediction heads for semantic and instance segmentation. The model underwent comprehensive validation on publicly available, machine learning-ready point cloud datasets. Additional analyses assessed model adaptability to different resolutions and performance across canopy layers. Our results reveal that point cloud sparsification as an augmentation strategy significantly improves model performance. It extends the model's capabilities to sparse LiDAR data and boosts detection and segmentation quality in dense, complex forest environments. Notably, the model showed consistent performance for point clouds with densities >50 points m-2 but exhibited a drop in performance at the sparsest level (10 points m-2), mainly due to increased omission rates. Benchmarking against current state-of-the-art methods established the proposed model's superior performance on multiple open benchmark datasets. For example, on the LAUTx dataset, our method outperformed Point2Tree and TLS2trees by ≈20-30% in detection rate, omission rate, commission rate and F1 score. Our experiments also set new performance baselines for the Wytham Woods and TreeLearn datasets. The comparison highlights the model's superior segmentation skill, mainly due to better detection and segmentation of understory trees below the canopy, with reduced computational demands compared to other recent methods. In conclusion, the present study demonstrates that it is indeed feasible to train a sensor-agnostic model that can handle diverse laser scanning data, going beyond current sensor-specific methodologies. Further, our study sets a new baseline for tree segmentation, especially in complex forest structures. By advancing the state-of-the-art in forest lidar analysis, our work also lays the foundation for future innovations in ecological modeling and forest management.

Simplified Tree Competition Analysis: Introducing TreeCompR for Inventory Data and 3D Point Clouds

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Introduction/Aim:

The 2018/19 drought in Central Europe has highlighted the importance of identifying and understanding factors that influence tree vitality, especially in the face of future climate uncertainties. The creation of variability within tree neighbourhoods or the release of competition are discussed as factors influencing the resilience of forest stands. Therefore, we need to assess the competitive situation of trees. However, collecting ground-based inventory data is time-consuming and often difficult in dense forests. Furthermore, there is no single universally applicable index for quantifying competition, which complicates the decision-making process. To guide users through the different options of competition indices (CIs), we here present the open-source R package *TreeCompR*, which can process 3D point clouds in different formats as well as in situ inventory data. This open-source tool is designed to assist users in selecting appropriate competition indices (CIs) and data options for assessing tree competition and structural variability in forest stands.

Methods:

With *TreeCompR*, users can choose between point cloud-based and conventional distance-dependent CIs. The package provides fast output of different CIs for all trees within a plot or specified target trees. We demonstrate the functionality of the package through application examples and a comparison of point cloud-based (e.g. search cone method) and distance-dependent indices (e.g. Hegyi index). We also advise on how the data should be pre-processed, assess potential uncertainties associated with these methods and suggest strategies to mitigate them.

Results:

We used the tools of *TreeCompR* to analyse data from mobile and airborne laser scans and to assess the competitive status and neighbourhood structure of 308 European beech trees. The trees are distributed across 13 forest sites in northern Bavaria, Germany, along an environmental gradient. All sites were affected by the 2018/19 Central European drought and differ in crown damage and vitality status. The CIs were all found to correlate with structural parameters such as crown projection area (CPA) or box dimension (D_b) of the target trees, while the traditional distance-based approach appears to be more effective in predicting structural parameters than the point cloud-based CIs. We found a high sensitivity of CI values to the chosen search radius or the number of neighbouring trees, which can be highly dependent on the data source and pre-processing.

Conclusion:

TreeCompR serves as a valuable tool for ecologists and foresters, facilitating efficient and accurate assessment of tree competition and structural variability within forest stands. Users are free to choose whether to use original 3D point clouds or inventory data (ground-based or derived from point clouds), depending on their research questions and data availability. We recommend that certain types of data (e.g. from airborne laser scans) should be supplemented by ground observations and that the search radius should be adjusted according to the average crown diameter of target trees.

Developing a Forest Fire Diagnostic Model Utilizing Satellite Imagery

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Forest fires exert a significant impact on Earth's ecological systems, resulting in consequences such as deforestation, habitat degradation, and adverse effects on environmental, economic, and social domains. The restoration of areas affected by forest fires demands substantial time and effort to return them to their original state. Proactive identification of areas prone to forest fires is crucial for minimizing the damage caused by such incidents.

In this study, a forest fire diagnostic model was developed to enhance the precision of forest fire risk predictions. The model utilized remote sensing data and human activity maps. To gauge the dryness of the land surface, the Vegetation Temperature Condition Index (VTCI) was employed, and density maps of roads, buildings, and cropland were incorporated for the human activity maps. The algorithm of the model was based on the Random Forest classifier, and it was trained on forest fire occurrence data from 2016 to 2020 across South Korea.

To assess the actual performance of forest fire forecasting, short-term forecasts for a 3-day period were conducted from February to May 2023. The model successfully predicted 80% of forest fires during this evaluation period.

Studying the Influence of Park Attributes on Urban Temperature: A Remote Sensing Approach in Christchurch, New Zealand

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Introduction/Aim: The urban thermal environment is becoming increasingly unfavourable for city dwellers due to the growing trend of urban intensification. Under this scenario, urban parks can be identified as an integral element of urban landscape that moderate urban temperature and improve the human outdoor thermal comfort. However, the complex relationship between park attributes and temperature variables remains insufficiently explored. Furthermore, there is a notable research gap in New Zealand concerning studies on the urban thermal environment, which is becoming increasingly urgent in the context of global warming. Remote sensing can be a powerful tool to address this gap by measuring land surface temperature, vegetation cover and vegetation structure. Thus, this research is executed to investigate the impact of urban park attributes on air temperature and Land Surface Temperature as key as key temperature variables related to urban thermal environment using Remote sensing approaches.

Methods: The fieldwork for the study was conducted during the 2023-2024 summer season, focusing on parks in Christchurch, New Zealand. Sampling plots were established randomly throughout parks in urban area. Air temperature and wind speed were recorded using Kestrel 5500 portable weather station. Soil moisture and temperature were also collected during the field survey. Vegetation structure was measured with aerial LiDAR, while aerial imagery was used to describe land cover. Finally, Landsat imagery was used to estimate land surface temperature. An analysis was conducted to determine the effect of vegetation structure and configuration on land surface temperature and measured air temperature.

Expected Results: It is anticipated the results of the analysis will identify key factors that influence the urban thermal environment.

Conclusion: Findings will explore the complex interplay between urban greenery and urban thermal environment regulation. Replacing ground-based measurements of vegetation structure and air temperature with remotely sensed data will provide more efficient and cost-effective means of data collection. This advancement will open opportunities to incorporate outdoor thermal comfort considerations into urban planning processes.

Linking Canopy and Surface Fuels: Advancing Spatial Mapping in Fire-maintained Forest Ecosystems

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Introduction/Aim:
Large-scale mapping of canopy, surface, and ground fuels is needed to support forest management decisions, fire and smoke modeling, and carbon monitoring. Remote sensing, particularly laser scanning systems, is the most cost-effective technology for describing overstory biomass. However, direct estimation of surface and ground fuels is hindered by canopy occlusion and the low sensitivity of these sensors to discriminate the ground from dead and live vegetation on the lowest stratum of the forest floor. Canopy fuels influence the accumulation, structure, and composition of dead surface fuels (i.e., litter and downed woody debris), while these surface fuels further break down and decompose into duff (i.e., partially to fully decomposed organic material). Methods that couple surface and ground fuel inputs to the overstory tree crowns and apply ecological concepts to quantitatively describe the fuel accumulation process have demonstrated potential to capture much of the inherent heterogeneity observed on the forest floor.

Methods and Results:
Herein, we describe a comprehensive modeling framework for mapping surface and ground fuel accumulation by leveraging information on canopy structure characterized by airborne laser scanning (ALS) data. Study sites are fire-maintained longleaf pine forests located in Florida, Georgia, and South Carolina (southeastern USA), where prescribed fire is used as a management tool. Our methodology involves first segmenting tree crowns from ALS data and mapping branch and foliage biomass. We partition the total crown biomass into components corresponding to leaves and fine branches using allometric equations and TLS-derived estimates of the proportion of wood components that are in turn upscaled to the tree crown objects segmented from ALS data. We quantify both annual production of these fine fuels and their accumulation using a spatially explicit implementation of the Olson accumulation model (Olson, 1963). The duration of surface fuel accumulation is defined with prescribed fire records and decomposition rates are derived from climate information and literature. Coarse woody debris is incorporated on the surface fuel pool by defining mortality rates assessed from National Forest Inventory (NFI) plot data. We finally simulate duff formation from the breakdown of all these surface fuel components using a soil organic carbon model (Liski et al., 2005).

This modeling workflow enables mapping fine fuel loads at high spatial resolution (≤ 5m), partially resolving the limitations of current methods to describe the inherently heterogeneous surface fuelbed layer in a spatially explicit manner. This project remains in progress to improve the estimates of the different fuel components across different locations. We aim to expand this modelling workflow to other ecosystems such as western sites of the US and applications such as simulation of fuel loads with synthetic forests.

Conclusion:

Models such as this can already support decision-making to balance management and ecological needs in the study sites, ensuring the good functioning and maintenance of the ecosystem services, increasing fire resilience, and reducing fire risk.

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Forest Response to Extreme Drought and Thinning: UAV and ECOSTRESS-based estimates of Canopy Temperature and Evapotranspiration

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Semi-arid forests across the southwestern USA are being treated with mechanical thinning and prescribed burning to reduce the risks of catastrophic forest fires. In Arizona, the US Forest Service (USFS) is treating approximately 2 million ha over 20 years via mechanical thinning and prescribed burning (USDA, 2013). To measure the effects of forest thinning on drought resiliency, we have been monitoring thinned and non-thinned ponderosa pine forests in northern Arizona. Our study period since 2018 has included extreme drought year 2021 as well as average precipitation (2018) and wet years (2022-2023). Our forest spectroscopy data and extensive, hourly soil moisture data since 2018 have demonstrated that the thinned stands had significantly greater soil moisture than non-thinned stands in 2021, 2022, and 2023 as well as significantly greater vegetation water content. These differences were further enhanced during the extreme drought year 2021.

Using an unoccupied aerial vehicle (UAV) thermal sensor and ECOSTRESS satellite images of land surface temperature (LST), we monitor thinned and non-thinned forest canopy temperature response to drought. The UAV LST and ECOSTRESS LST estimates in average and drought years consistently indicate significantly higher LST in thinned stands than non-thinned stands. During the regional drought in 2021, thinned stands in both datasets continued to have significantly higher canopy temperatures, but non-thinned forest canopy temperature increases are significantly greater than thinned canopy temperature increases. This indicates that thinned forest canopy temperatures are better buffered than non-thinned stands during extreme drought. Interestingly, LST estimates in the non-thinned stands are significantly different between the two datasets: ECOSTRESS data indicate much lower LST in non-thinned stands compared to the UAV LST. This might be partially due to the geolocation accuracy of the ECOSTRESS data, which has positional errors of up to several pixels, since our non-thinned forest covers a relatively small area.

Using ECOSTRESS evapotranspiration (ET) data (Fisher et al., 2020), we also estimate thinned and non-thinned forest ET. Consistent with the temperature results, ECOSTRESS ET data show significantly greater ET in non-thinned stands than thinned stands across years. Our study area, which was thinned in 2018, still show significantly lower ET in thinned stands compared to non-thinned stands. While non-thinned stands show significantly greater ET due to high tree density and basal area (Simonin et al., 2007; Hamberg et al., 2022), trees in these stands compete for limited soil water. Taken together, our results indicate that non-thinned stands with high evaporative cooling demands experience significantly greater water stress than thinned stands during drought years. Furthermore, in water-limited Arizona, the thinning has resulted in water savings via ET reductions by 3mm/day in each ECOSTRESS pixel, on average. We are field-validating the ECOSTRESS ET results using a large network of sapflow sensors across our study area. Our results indicate ECOSTRESS data can be used to understand the ecohydrological impacts of regional-scale thinning efforts on drought resiliency across larger spatial extents.

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A moderate resolution 3D forest structure map of New Zealand

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Introduction/Aim:
New Zealand's unique flora and challenging landscapes have long made mapping the vertical structure of its woody vegetation particularly difficult. The complexity of the nation's forest ecosystems, dense foliage, and steep, varied terrain necessitate advanced methods for accurate vegetation structure characterisation. Addressing these challenges, a novel 10-m spatial resolution map that captures the height and cover of New Zealand's forest and woodland structure has been developed by integrating Sentinel-2, Sentinel-1, and Global Ecosystem Dynamics Investigation (GEDI) data sets.

Methods:
The mapping methodology leveraged Sentinel-2 optical imagery processed through time series modelling to construct a barest earth mosaic, critical for discerning forest structure across dense canopies and rugged terrains. Sentinel-1 SAR imagery, processed using a Radiometric Terrain Correction (RTC) model, mitigated topographic distortions prevalent in New Zealand's landscape, improving the accuracy of the vegetation backscatter interpretation. The higher spatial resolution of Sentinel-1 and -2, compared to previous datasets like Landsat ETM+ and ALOS PALSAR, allowed for a more detailed detection and characterisation of the variability in the structural types across the country. These data were combined using a singular value decomposition approach and then segmented into approximately 1 ha areas with similar structural typologies. A nationwide clustering approach was applied to recover segments with similar cover and backscatter areas. Finally, GEDI waveforms were aggregated within these clusters to provide fine-scale three-dimensional vegetation structure, adding vertical foliage profiles and structural metrics to the clustered segments, such as the 95th percentile height, mean height, and height to maximum vegetation density.

Results:
These classifications were applied nationwide, leveraging the class uniformity to extrapolate GEDI-derived metrics across different landscapes. Satellite-derived structural estimates were validated against field data from airborne LiDAR across various forest types and demonstrated high congruence. Variability within GEDI profiles were consistent across classes, with differences typically attributed to natural or anthropogenic changes. The result was a comprehensive national map of vegetation height, further enriched with coverage estimates to refine New Zealand's structural classifications.

Conclusion:
Integrating these diverse datasets—optical, SAR, and lidar—proved critical for segmenting and classifying land cover, extracting biophysical properties, and making significant strides in the comprehensive mapping of New Zealand's forests. Such enhanced forest structure mapping has broad applications, including effectively quantifying carbon stocks, biodiversity conservation, forest health assessments, change monitoring, and informing environmental policy decisions. This study lays the groundwork for incorporating next-generation satellite and lidar technologies to advance large-area forest structural assessments in New Zealand.

Spaceborne Forest Disturbance Detection in Central Europe using Transformers

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Introduction: Central European forests provide important ecosystem functions like climate regulation and carbon storage. Yet, climatic extreme events, which are becoming more frequent in times of climate change, led to major forest damage in recent years. The hot drought of the years 2018 until 2020, for instance, resulted in signs of damage in almost 80% of the trees in German forests. The weakened trees, then, are more susceptible to co-morbidities such as bark beetle infestations. This vast extent of forest damage cannot be monitored efficiently using ground data alone, and multispectral satellite image time series (SITS) may be an alternative. Most existing remote sensing-based forest disturbance detection methods follow one of two main approaches: Firstly, near real-time monitoring tools (e.g. BFAST Monitor, CCDC, Fordead) use an undisturbed reference period for model fitting and try to detect deviations from model predictions in the subsequent monitoring period. These methods, thus, rely on the assumption that the training period does not exhibit disturbance. Secondly, temporal segmentation algorithms identify break points and trend changes retrospectively. The segmentation is usually done on interpolated (e.g. BFAST) or seasonally aggregated (e.g. LandTrendr) univariate time series.

Methods: Here, we use a third type of approach, known from machine learning: time series classification. These methods classify the whole time series into undisturbed or disturbed forest pixels. A potential advantage is that the trained models do not need an undisturbed reference period for each pixel, as they have been fitted on a large amount of training data. In this study, we apply transformers, a state-of-the-art Deep Learning (DL) architecture, which have evolved as a promising tool for time series classification in remote sensing, on Sentinel-2 (S2) time series. Transformers are capable of establishing (the strength of) temporal links between satellite observations (such as lag effects between drought stress and subsequent tree dieback) by applying the so-called *self-attention* algorithm. Our Transformer model can process multivariate time series as input and does not need interpolation or gap filling. We train the model in two steps: *pre-training* was conducted with a high amount of time series with labels of medium accuracy of disturbances in German forests, while *fine-tuning* contained a smaller amount of highly accurate forest damage labels of Germany and Luxembourg. We compare three setups: *DL base* (using ten S2 bands as model input), *DL IND* (using ten vegetation indices) and *DL +IND* (using both).

Results: Preliminary results show that DL is capable of detecting dieback events of as small as 20 m² in the 100 m² pixels. Explainable AI indicates that DL base can distinguish between signal and noise in SITS expressing lag effects. Since DL base performs similar to the other DL setups, our results indicate that DL methods are capable of disentangling a complex signal given by ten different S2 bands instead of relying on handcrafted vegetation indices.

Conclusion: We conclude that using S2 time series in combination with Transformers are a viable approach to effectively provide timely and small-scale forest disturbance information in Central European forests.

Assessing the Ability of Open Access Remote Sensing Data and Machine learning to find Spatial and Temporal Patterns of Woody Plant Encroachment in Savanna Ecosystems

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Woody plant encroachment (WPE) is a global phenomenon that is affecting grasslands, savannas, and rangelands at an accelerating rate. WPE refers to a shift in the dominant vegetation of an ecosystem from grasses to woody species and yields mixed effects on ecosystem services and local economic activities. Many of these effects vary based on the physiology and relative abundance of a particular woody species associated with the encroachment. Given the scale of WPE in the United States, there is a pressing need to improve the methods used to quantify the extent of WPE. The rise of open access data and machine learning methodologies provide new opportunities to study WPE at the scales necessary to define the spatial and temporal trends of WPE. We seek to identify the specific advantages offered by different remote sensors coupled with machine learning to guide future research about WPE. We will use a UAV to collect our multispectral and LiDAR data, and a small aircraft to collect the hyperspectral data. Our open access imagery will be downloaded from Sentinel-2. Our overall aim is to generate a map of the distribution of our two study species at the Martin Ranch in Menard, Texas – ashe juniper (*Juniperus ashei*) and honey mesquite (*Prosopis glandulosa*). The data will be classified using a pixel-based approach with Random Forest in R using the *caret* package. Our models will be trained on 70% of our pixel data, which will be selected based on the unique phenology of our two study species. Model performance will be validated using the remaining 30% of the training pixels and is expected to yield at least 80% accuracy or a 0.61 kappa value at the pasture scale. The final models will be subject to a pairwise comparison to assess differences in performance for each sensor type. Our findings will guide future efforts in identifying remotely sensed data with the highest cost-utility for use in machine learning applications. In addition, the results will identify the local extent and magnitude of WPE, as this phenomenon affects numerous ecosystem processes such as carbon storage, water quality, and support for biodiversity. The improvement of species-specific mapping will be beneficial for understanding changes brought forth by WPE, and future work will build upon these methods to better quantify carbon in non-forest ecosystems to assess progress in meeting sustainability goals.

Detecting Drivers of Forest Canopy Mortality following Drought

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Introduction/Aim:
Why do some trees die during droughts while others seem to be doing just fine? Many studies have explored the influence of site characteristics on forest mortality at local monitoring sites, but few have used a detailed mortality dataset at a large spatial scale, yet.

Methods:
Here we created a new, large dataset of canopy mortality acquired over the years 2017-2020 for the country of Luxembourg (~2500 km²) within Europe, using a deep learning image segmentation and classification algorithm. The dataset contains all dead standing tree canopies throughout Luxembourg at a resolution of 20 cm and differentiates between conifer and broadleaf trees. We explored why canopy mortality during the drought summers 2018-2020 was higher on certain sites throughout the country, while trees seemed to be less effected in other areas. To this end, we tested the influence and interaction of different site characteristics pertaining to topography, stand structure and soil using a generalized additive model.

Results:
Canopy mortality was ten times higher in 2020 compared to 2017, increasing from 0.64 km² in 2017 to 7.49 km² of canopy area in 2020. Additionally, canopy mortality in conifers was much higher and highly clustered. We found that the distance to previously dead trees played an important role in explaining mortality patterns in conifers, and this effect was most pronounced for the year 2019. This is likely linked to the spread of bark beetles (*Ips typographus*) in the drought-prone and extensively managed forests. In broadleaf trees in which mortality appeared scattered throughout the forests, we found tree height as a driver of mortality with trees above 20 m having a higher mortality rate. Canopy mortality was generally more pronounced on soils with little water storage capacity, while topographic variation played only a minor role in explaining the observed mortality patterns.

Conclusion:
The patterns of tree mortality following three consecutive dry years were not explained by a single factor, but were clearly affected by a multitude of environmental and stand characteristics intertwined at the landscape-scale, which might be easily missed by discreet monitoring sites. This highlights the importance of developing tools to study tree mortality at larger scales in order to develop management strategies that promote tree resilience to future drought events.

Preliminary integration of Satellite and Forestry Inventory Data to Predict Fire Hazard in Estonian Forests

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Introduction/Aim:

Forests are vital ecosystems threatened by increasing disturbances due to global climate change, playing a crucial role in sustaining biodiversity, biogeochemical cycling, climate regulation, and various human activities. In the Baltic states, forests cover 43% of the total land area, with Estonia alone accounting for 63% of its land area, exhibiting a growth trend since 2000. Nevertheless, forests in the Baltic region face challenges posed by climate change, human settlements, and historical land use practices such as agricultural clearance and abandonment. These disturbances can significantly alter forest composition and functioning, affecting carbon sequestration capabilities.

Therefore, understanding and predicting fire hazards in Estonian forests is critical for effective forest management and conservation efforts. In this context, satellite-based and forestry inventory data were integrated to predict fire hazard classes in Estonian forests, using various modelling approaches.

Methods:

A Sentinel-2 collection including all images during the summers of 2018 and 2019 was created; we considered the historical average dates (i.e., between 4th June and 5th September) for the summer season for this filter. From this collection, the average value of 11 vegetation indices (VI) containing red, green, near-infrared and red-edge data was calculated and extracted for each entry. In addition, the same procedure of zonal statistic was employed on the Canopy Height Models (CHM) provided by the Estonian Land Board to obtain structural descriptors of the forest stands. Finally, we trained RF classification models to discriminate fire danger classes using forestry inventory, Sentinel-2 VIs, and ALS CHMs. We divided the datasets as follows: the multispectral dataset, which contained vegetation indices and their derived metrics (CV and GLCM dissimilarity); the CHM dataset, which contained height mean, CV, and dissimilarity of structural descriptors; and one dataset, integrating both of them.

Results:

The dataset included 251,738.2 hectares and 203,459 entries. Overall, 34.4% of plots were considered "low" fire hazard ("IV"). The dataset comprises 8.9% "very high", 14.8% "high", 27.5% "intermediate", and 14.4% "very low". The integrated dataset had the highest performance among the evaluated models. The average classifier accuracy was 73.2%. This fire hazard classifier was the most accurate, with 100% accuracy for class 1 and 74.5% for class 4. Class I fire hazard was the best detected. Class IV had the lowest and most inconsistent detection rates. The strongest contribution VIs were RTVI and SRRE. NDVI and OSAVI were unimportant for fire danger modelling. Models using ARVI2 and MSR670 dissimilarity indices had moderate performance. Lastly, CHM-based metrics enhanced model performance slightly but were crucial.

Conclusion:

Integrating multiple data sources, including satellite imagery and forestry inventory data, enabled us to understand moderate fire hazard dynamics in Estonian forests. Robust monitoring and management strategies are essential to mitigate disturbances' impact. Future research should explore the exclusive utilization of satellite optical data and incorporate drone data for enhanced monitoring and validation of fire hazard assessments.

Maximizing Urban Tree Benefits in Christchurch Through Automated Inventory Using Remote Sensing

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Introduction/Aim: Urban trees are valuable green assets, playing a vital role in improving the quality of urban environment and human well-being through the provision of ecosystem services. Given their critical contribution to human well-being, it is imperative to monitor and measure these ecosystem services. While urban forest ecosystem services cannot be directly measured on the ground, they can be effectively modelled by quantifying the structure and composition of the urban forest.

Ground-based tree inventories are time-consuming, costly, and reliant on skilled labour and susceptible to human error. In this regard remote sensing offers quick, cost effective and systematic ways to measure urban forests over expansive areas. Free wall-to-wall ALS data in New Zealand can potentially be used to accurately quantify the urban forest structure. This research aims to utilize ALS data for compiling an automated urban tree inventory, which can be seamlessly integrated with ground-based models for modelling various ecosystem services.

Methods: The proposed methodology involves employing ALS data to estimate tree structural attributes for generating a tree inventory for urban parks in Christchurch, New Zealand. For this, individual tree point-cloud segmentation is performed to derive tree height, crown width and crown base height. These ALS derived parameters further assist in predicting stem diameter and species through the use of statistical models. Ultimately, the performance of ALS derived tree metrics is evaluated against the ground measurements.

Results: It is anticipated that using ALS data the structure of the urban forests can be accurately quantified over a large scale as opposed to limited ground-measurements.

Conclusion: This study has the potential to optimize urban forest assessment and management in Christchurch by providing a systematic approach to generating an urban tree inventory for modelling their ecosystem services. This would enable the decision makers in making informed choices aimed at enhancing urban tree benefits, thereby promoting their equitable distribution across the city.

Data.GEO-TREES - A Global Harmonised in-situ Data Repository for Forest Biomass maps Validation

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Monitoring of forest biomass and its changes is critical for understanding climate and ecosystem dynamics. Recently, innovative space instruments specifically designed for this task have been launched, with more expected soon. These missions depend on ground-based estimates for calibrating algorithms and validating products. The GEO-TREES (https://geo-trees.org/) is an international cooperation to maintain a global in-situ forest biomass database to support earth observation and to encourage investment in relevant field-based observations and science. Its mission is to bridge the gap between the remote sensing (RS) community and ecological and forest inventory experts working on the ground, fostering mutual benefits.

For the RS community, GEO-TREES offers partnership with leading ecological research teams and networks that manage permanent forest plots. This collaboration aims to resolve data sharing challenges and standardize biomass data flow from individual tree measurements to plot-level aggregation. Ecologists, in turn, gain from enhanced access to global biomass data, standardized data collection protocols, identification of data gaps, and potentially increased funding opportunities to address these gaps and data deficiencies.

GEO-TREES is an inclusive initiative, inviting further collaboration from various networks and teams. Its online database, accessible for plots with author permission, includes essential information such as plot coordinates, canopy height, and above-ground biomass of trees, covering areas of 0.25 ha or larger. Larger plots are subdivided into smaller plots to capture variability in height and biomass.

Adhering to the CEOS Aboveground Biomass Land Product Validation protocol, GEO-TREES strives to establish a network of biomass reference measurement (BRM) sites. Core BRM sites are distinguished by comprehensive measurement criteria, including tree inventory across ten 1-ha permanent sample plots, airborne lidar scanning over 1,000 ha, terrestrial lidar scanning across three hectares, and the integration of weather stations and automated soil moisture monitoring.

Data.GEO-TREES database is essential for validating and calibrating satellite observations and various models. A comparison of plot biomass data with existing global and regional maps (incl. CCI Biomass, NASA JPL, ICESat-2) reveals significant uncertainties in biomass estimation, highlighting the importance of initiatives like GEO-TREES in improving the accuracy and reliability of biomass measurements.

This study is supported by the European Space Agency FRM4Biomass project (RFP/3- 18237/23/I-EF-bgh).

Identifying the Drivers of Biomass Change in European Forests: Insights from Remote Sensing and Geo-Wiki Analysis

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Forest biomass stock and its changes serve as crucial indicators of ecosystem health, biodiversity, and the effectiveness of climate change adaptation and mitigation efforts. With the advancement of remote sensing technology and data processing techniques over the last decade, our ability to monitor these changes has significantly improved. However, the validation of these changes and the identification of their underlying causes often lack accurate quantification.

The European Space Agency's Climate Change Initiative (ESA CCI) Biomass project offers above-ground biomass (AGB) maps with a spatial resolution of 100 meters, covering the years 2010 to 2020. This product benefits from the integration of diverse remote sensing tools, including radar, lidar, and optical sensors. The set of maps includes the standard deviation of AGB estimates and a quality flag for AGB changes. However, set of sensors used for AGB estimation vary from year to year, that affect the reliability of biomass change analysis.

To validate and identify the drivers behind these reported biomass changes, we employed Geo-Wiki.org, a renowned tool for the visual interpretation of high-resolution imagery and vegetation indices. This approach allowed us to check if changes detected by CCI Biomass is visible, and to discern the drivers of changes, including natural regrowth, forest management (planting, thinning, harvesting), natural disturbances (fires, pests, wind, flooding) and land use change. Our methodology employed a threefold stratification based on geographic regions, the magnitude of biomass changes (loss and gain), and the reliability of change detection (indicated by a quality flag). This stratification enabled the estimation of area changes attributable to specific drivers at a regional level.

Our findings indicate that 92% of forest gains in Europe were due to reforestation or natural growth, 6% to afforestation, and 2% to urban expansion, tree crops, and agroforestry. Biomass losses revealing that 72% are associated with forest management (harvesting or thinning), 12% with land use change or activities outside of the forest (infrastructure, cropland, tree crops), 11% with wildfires, 4% with insects and deceased, 1% with windthrow, and 1% with other natural disturbances.

A visual inspection of the CCI Biomass change product revealed that roughly half of the reported changes were not verifiable using freely available very high-resolution images. This discrepancies arising from both methods - the invisibility of certain changes in the images and false detections due to utilization of different sensors over the observed period.

This work is supported by the Horizon Europe EYE-CLIMA project (101081395) and the European Space Agency's FRM4Biomass project (RFP/3-18237/23/I-EF-bgh).

Remotely Sensed Canopy and Litterfall Trends of Longleaf Pine Plantations in South Georgia, USA

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Introduction/Aim:
In the southern USA, longleaf pine plantations are valued for a regionally specific non-timber commodity, ‘pine straw’, where recently fallen needles (i.e., annual litterfall) are raked and sold as landscaping mulch. For instance, in 2022 Georgia-produced pine straw was valued at USD $127 million. Due to its value, there is novelty to leverage satellite imagery to understand longleaf pine canopy dynamics to describe how site fertility affects canopy production and to predict future pine straw yields. Here we present a framework to use Landsat 8 and 9 derived vegetation indices to predict longleaf pine plantation litterfall.

Study background:
Our study involved 84, 0.04 ha plots on two eleven-year-old high fertility sites and two eleven-year-old low fertility sites in south Georgia. The high fertility sites had greater standing tree volume (20.63 m^{-3} ha^{-1}) and were at canopy closure, where the low fertility sites had lower standing volume (9.18 m^{-3} ha^{-1}) and were further away from canopy closure.

Results:
Using generalized additive models (GAMs) we determined that predictors like day-of-year (DOY), date, and fertility (high vs. low) explained the most variation in normalized difference moisture index (NDMI, $R^2 = 0.58$) and best represented the biological patterns of litterfall when compared to other popular indices like enhanced vegetation index-2 (EVI-2, $R^2 = 0.19$) or the newer near-infrared reflectance of vegetation (NIR_v, $R^2 = 0.51$).

We then used a GAM to relate NDMI values for each plot to ground-collected leaf area index (LAI, 684 total plot-level means) values for growing-$season_{2023}$. NDMI, LAI collection month, and fertility were used as predictors, and explained 63% of variation in LAI.

Next step was to relate LAI to litterfall biomass, but there was a lag between litterfall and LAI data collection. For example, due to a needle lifespan of ~18-months, collected $December_{2022}$ litterfall samples (84 plot-level means) represented canopy conditions and LAI from growing-$season_{2021}$. So, the above LAI model was used to predict LAI_{2021}.

Another GAM was then fitted to predict $litterfall_{2021}$ biomass using predicted LAI_{2021} and site fertility as covariates. The GAM explained 75% of the variation in $litterfall_{2021}$. Partial effects from the model also demonstrated that high fertility litterfall trends were non-linear while low fertility litterfall trends were more linear.

Conclusion:

Our workflow provides structure for how longleaf pine plantation managers, who are likely interested in pine straw yields, can leverage current year imagery to predict longleaf pine litterfall in the subsequent year.

Use of Planet Cubesat Imagery for Forestry applications: A review and case study

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Satellite remote sensing has become an integral tool for forest management, allowing decision makers to integrate data over large spatial areas at regular time intervals. However, data acquired from conventional satellite systems often comes with trade-offs between spatial and temporal resolution. PlanetScope – a commercial satellite system developed by Planet Labs in 2014 – has attempted to overcome this trade-off by integrating data acquired from over 200 CubeSats to provide near daily coverage of the Earth at approximately 3m spatial resolution. Such datasets pose unprecedented opportunities for measuring and monitoring the world's forests.

We present a systematic review of how Planet data has been used over the past decade in forest applications. We analyzed over 100 peer-reviewed publications to understand the forest application, geographic area of focus, methods, and outcomes of PlanetScope data in forestry. Our review found that PlanetScope has been used for a wide variety of forest applications, which include phenology monitoring, land cover classification, tree species prediction, and modelling forest structure. Broadly, the preeminent use has been in the monitoring and characterization of different types of forest disturbances. In particular, researchers have incorporated Planet data into pipelines that enable continuous monitoring of forest disturbances at fine spatial scales. When comparing to satellites such as Landsat, models developed using PlanetScope data outperformed those based on moderate spatial resolution optical data. A review of PlanetScope applications also found evidence of challenges related to data quality, with inconsistent radiometric calibration between satellites being an area of particular concern. We conclude with a case study – by undertaking a novel approach to radiometric normalization which can be applied to single or multiple scenes of PlanetScope data to detect disturbances in a natural boreal forest environment in Canada.

Predicting countrywide growing stock volume using airborne laser scanning, Landsat time series, and national forest inventory data in Japan

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Introduction/Aim:
Predicting large-scale forest structural attributes is important for sustainable forest management. Airborne laser scanning (ALS) data has been acquired in many regions over the past few decades; however, it is usually collected regionally across different projects and does not cover the entire country. Although ALS-derived three-dimensional information can aid an accurate prediction of forest structure, such as growing stock volume, the prediction methods using spatially and temporally biased ALS data have not been fully investigated for wall-to-wall national-scale mapping. In this study, we investigated and assessed the methods for predicting growing stock volume in Japan for 1990–2020 using ALS data collected in different regions, national forest inventory (NFI) data, and Landsat time series data.

Methods:
We collected ALS data acquired in different regions and years across Japan, which covers 4.6 million ha (i.e., 12% of the total land area of the country) in total. We processed the original point cloud data to generate area-based metrics at 30 m spatial resolution in each ALS extent through the ground/non-ground classification, digital terrain model generation, and point normalization. Then, the latest NFI data was used to build a prediction model for growing stock volume in the ALS extent. In this stage, we used area-based metrics from ALS and growing stock volume from NFI data in a generalized linear model for prediction. After building the NFI-ALS model, we predicted growing stock volume for ALS extent and then used them to build second stage models for wall-to-wall national-scale mapping. We derived predictor variables from Landsat time series data for 1985–2021, the forest disturbance map, and topographic data. We implemented Continuous Change Detection and Classification and LandTrendr algorithms using Landsat time series data to derive times series variables covering the entire country. This study employed a deep learning algorithm, U-net network, to predict ALS-derived growing stock volume. The prediction accuracy was evaluated using the validation data from ALS-derived growing stock volume and independent field surveys.

Results:
The root mean squared error (RMSE) of the U-net prediction model was 147.4m^3/ha (relative RMSE of 37.4%) based on validation data from ALS-derived growing stock volume. The independent field survey data showed possible regional differences in prediction accuracies. The mapping results over the country indicated that there were growing stock volume of 8.65 billion m^3 in 2020, which is almost the same amount estimated by the latest NFI data (i.e., 8.62 billion m^3). The overestimation was observed for the estimates in 1990, which might be caused by a lack of forest disturbance information prior to 1985.

Conclusion:
This study shows a potential strength of ALS data that were acquired in different regions across the country to predict wall-to-wall forest growing stock when combined with NFI and Landsat time series data. Although the prediction accuracy might be lower in 1990, spatially explicit estimates from this study can improve the understanding of countrywide forest dynamics.

193

Applications for remote sensing in the voluntary forest carbon market

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Although the Voluntary Carbon Market (VCM) is still relatively small today, valued between $1 - $2B/year, the global compliance market scale is $850B or more. There is reason to be optimistic about the growth potential of the VCM as the number of corporations making emission-reduction and net-zero commitments continues to increase. With this growing demand for carbon credits, an influx of remote sensing solutions for carbon quantification have entered the market. When compared to ground-based inventory solutions, remote sensing could offer higher accuracy for carbon inventory which may support greater transparency, and ultimately, development of higher-quality forest carbon credits available. Because of this, it is vital that the remote sensing community understand the complexities of the forest carbon project development so that scientists can support the inclusion of remote sensing as a carbon quantification tool in forest carbon projects. This talk will provide an overview of the process of developing a high-quality forest carbon project, highlighting how remote sensing can play a role in forest carbon quantification.

Beyond Ice: NASA’s ICESat-2 Spaceborne Lidar Mission for Land and Vegetation applications

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Introduction/Aim:
NASA's Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) mission emerges as a pivotal asset for studying land and vegetation applications globally. In this work, we provide a detailed overview of the ICESat-2 mission, including its instrumentation, data collection, and mission objectives, with a particular emphasis on its relevance to land and vegetation applications. We also provide a comprehensive literature review on ICESat-2 studies conducted worldwide, focused on land and vegetation applications. Herein, we have two specific objectives: (1) to perform a systematic literature review and analyse a broad spectrum of studies worldwide that have utilized ICESat-2 data for land and vegetation applications, and (2) to critically assess the current capability and limitations of ICESat-2 data for land and vegetation applications. applications.

Methods:
We analysed 203 peer reviewed articles worldwide found on Web of Science and Scopus databases and provided insights into the geographical distribution, methodologies, and outcomes of these research endeavours. Moreover, we identified gaps in the current state of research and proposed avenues for future investigation and technological refinement.

Results:
Overall, the use of ICESat-2 for land and vegetation applications has exponentially increased since 2014, with ATL08 being the most downloaded product from ICESat-2. The number of studies conducted in developed countries (n=81) and developing countries (n=91) were approximately similar, with some studies conducted in both developed and developing countries (n = 24). The majority of studies were conducted primarily on Temperate Broadleaf and Mixed Forests and Temperate Coniferous Forests. ICESat-2 land, and vegetation products have been predominantly utilized in forestry, terrain, and ecology studies. These studies have been published in various journals across disciplines, with remote sensing journals being the most prominent. Validation of ATL08 terrain elevation and canopy height products has been conducted at limited scales. Although improvements have been achieved with updated product versions, there is still a need for a more comprehensive evaluation of these products, covering a range of environmental conditions at a global scale. The development of the ATL18 products, along with new additions to the ATL08, will not only significantly expand but also broaden the utilization of ICESat-2 for land and vegetation applications, introducing novel uses such as wildlife habitat quality assessment and monitoring. Furthermore, the current repeat track retrieval capability of ICESat-2 will enable continuous and unique monitoring of land and vegetation changes, enhancing the detection and monitoring of disturbances, including those caused by fires.

Conclusion:
This comprehensive review article not only encapsulates the current state of ICESat-2 research for land and vegetation applications but also serves as a foundational guide for future investigations, highlighting emerging trends and potential research frontiers in the evolving landscape of Earth observation missions.

ICESat2VegR: An R Package for NASA's Ice, Cloud, and Elevation Satellite (ICESat-2) Data Analysis for Land and Vegetation Applications

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Introduction/Aim:
The ICESat-2 mission, launched on September 15th, 2018, was primarily designed to precisely measure the Earth's elevation of ice sheets, glaciers and sea ice. Since data became available in May 2019, the mission science team also made available geophysical data products, such as ATL08 highlighting its suitability for characterizing surface heights within vegetated land surfaces and calculating relevant vegetation metrics. The ICESat-2 instrument is sensitive enough to detect each photon, generating a photon cloud that demands the use of distinct processing tools and methods. Moreover, the data is distributed in HDF5 format using a specific hierarchical and relational schema, posing potential challenges in handling and analysis. In R programming language, there are currently no packages covering the most common land and vegetation analysis tasks for ICESat-2. Herein, we introduce a new R package to address this issue, providing functions for locating, downloading, visualizing, and processing land and vegetation data, while integrating both ATL03 and ATL08 ICESat-2 products

Methods:
The ICESat2VegR package is currently under development, aiming to provide an open-source tool for managing ICESat-2 data in land and vegetation applications. The package is accessible at https://github.com/carlos-alberto-silva/ICESat2VegR. It is designed to maintain a consistent naming pattern for its functions, starting with the product it is intended to work on, followed by the unit of analysis level and the operation it performs. All data read from ICESat-2 will utilize S3 and S4 classes for dispatching generic methods to the internal classes. This design ensures that functions like "clip" can be used for both ATL03 and ATL08 products, adapting to clip the data to the provided extents or geometry. The provided functions are tailored to enable users to develop their workflow entirely in R. They facilitate tasks such as locating, downloading, visualizing data, clipping, processing, and transforming data into widely known formats such as regular R data frames, data.table, GDAL raster and vector formats, or LAS point cloud format.

Results:
We have developed more than 40 functions that allow users to download, read, process, and analyze ICESat-2 ATL03 and ATL08 data. ICESat2VegR is also integrated with Google Earth Engine (GEE), enabling users to upscale ICESat-2 vegetation attributes using other sources of remote sensing data (e.g., Landsat 8 OLI, Sentinel 2A). The data processing workflow using ICESat2VegR can be summarized as follows: i) Find the data pairs for ATL03 and ATL08; ii) Download the data or access cloud-hosted data; iii) ATL03: Extract the photon attributes to the data.table data format; iv) ATL08: Extract land segment attributes to the data.table data format; v) ATL03/ATL08: Join both products to extract classified photons to the data.table data format; vi) Compute vegetation metrics within user-defined segment lengths; vii) Connect extracted ICESat-2 metrics with GEE for vegetation structure upscaling and wall-to-wall mapping.

Conclusion:
In this paper, we introduce and demonstrate the application of ICESat2VegR, a package designed for manipulating ICESat-2 data with a focus on land and vegetation applications. Being an open-source project, we actively encourage community participation, emphasizing that the package will undergo continuous development and is anticipated to incorporate additional features.

Enhancing Seedling Detection in New Zealand Forestry: A Multi-Datastream Approach

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Early detection of seedlings is crucial for effective silvicultural practices and accurate mortality quantification in New Zealand plantation forestry. However, the presence of dense weed populations within the forestry cutover environment presents a significant challenge in the development of accurate detection models.

Recent advancements in consumer-grade multispectral UAV technology, such as the DJI Mavic 3 Multispectral, offer a cost-effective solution for capturing high-resolution RGB and multispectral imagery simultaneously. This study addresses the limitations of existing New Zealand UAV seedling detection models by developing mixed-resolution detection models using both high-resolution RGB and multispectral imagery.

Focusing on one-year-old Pinus radiata and Pseudotsuga menziesii seedlings across diverse site characteristics, five trial sites were selected in the Blue Mountains (Otago, New Zealand). These sites, totaling 143.8 hectares, encompass a spectrum of topographic, vegetative, and crop health conditions. At a flight height of 65m, high-resolution RGB imagery achieved a spatial resolution of 1.77 cm/px, while multispectral datasets attained 3.03 cm/px.

Within the mapped area, an estimated 140,870 seedlings are present for annotation. In addition to imagery annotation, ground-truthing using survey-grade GNSS receivers recorded the precise locations of 1,612 seedlings in regions with challenging detection conditions. Furthermore, the ground-truthing process included qualitative assessment of the health status of the seedlings.

This study was conducted under operational conditions, with the model generated from this study intended for direct operational use in New Zealand forestry management. We hope this nuanced approach, incorporating these multiple data streams, not only facilitates the generation of more powerful training data but also enables a more accurate assessment of model performance. By combining high-resolution imagery with precise ground-truthed seedling locations and health status, our methodology aims to enhance the robustness and reliability of seedling detection models.

This holistic approach not only improves the model's ability to accurately detect seedlings in difficult conditions but also provides valuable insights into its effectiveness across diverse environmental conditions, ultimately advancing our understanding and application of remote sensing techniques in forestry management.

Preliminary examination of the collected data instills confidence in the potential for improved detection accuracy, especially in heavily vegetated areas, through the integration of multispectral and high-resolution RGB imagery. While the research is ongoing and results are pending, initial observations suggest promising outcomes for advancing seedling detection methodologies in New Zealand forestry.

Remote Sensing to deliver Government Forestry Objectives

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New Zealand faces a critical challenge in meeting its climate targets under the Paris Accord, with current projections indicating a significant shortfall in greenhouse gas emissions reduction. Without intervention, New Zealand will have to buy carbon credits on the international market to close this gap, and forestry removal have a role to play in meeting this target. Te Uru Rākau- New Zealand Forest Service (TUR-NZFS) is utilising remote sensing technology to mitigate climate change and deal with the devastating effects.

Te Uru Rākau- New Zealand Forest Service plays an important role in delivering this priority by administering New Zealand's Forestry Emissions Trading Scheme (ETS). The opportunity of utilising remote sensing technologies to support Forestry ETS process improvement and understanding of forest removals is a key research goal. The application of remote sensing will not only support ETS administration there are other applications such as rapid assessment of impacts and risk during adverse events.

The Maximising Forest Carbon Research Programme is exploring new technologies to measure forest carbon stocks more efficiently and cost-effectively. The programme recently completed a proof-of-concept trialling LiDAR remote sensing within the current Forestry ETS framework. Forestry ETS participants with ≥100 hectares are required to take field measurements to generate participant-specific carbon yield tables, used for emissions returns to determine a participant’s unit entitlement. One of the big issues with these field measurements is getting the right resources on the ground to measure forest plots. We are researching the ability of LiDAR to capture this data instead, as a cost-effective alternative to the current methodology, because many forestry companies already use LiDAR to estimate forest stocks. Alongside this research, reviewing satellite LiDAR products for carbon measurement capabilities is another TUR-NZFS research priority.

Following the extreme weather events of 2023, TUR-NZFS has used remote sensing to assist in response and sector recovery. In the initial response, we used Sentinel 2 imagery to assess silt deposition for scoping government recovery packages. We also used Planet Imagery to rapidly assess forest grant schemes for cyclone damage. Finding new gullies, which are notoriously difficult to reforest, is another priority for TUR-NZFS. Utilising imagery gathered for the cyclone event we are updating the mapping of gully erosion in Gisborne. Previous gully digitisation exercises for Gisborne commissioned by MPI were carried out for with imagery from 1957, 1997 and 2017, and now, post cyclone Gabrielle imagery is used to digitise all gullies showing signs of active erosion in the region.

Remote sensing technology holds immense potential for advancing forest carbon measurements in New Zealand. By improving our ability to monitor carbon stocks, we can develop better informed policy, improve the measurements used in developing the default carbon yield tables (for forests under 100ha), provide evidence of the impact of enhance forest management practices on removals, assist forest recovery in face of adverse events, and further contribute to our climate change mitigation goals.

Nationwide Modelling of the Forest Health and Mortality Risk by Fusing Airborne Laser Scanning Data, Satellite Imagery and Field Inventory Data

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Climate change results in warmer and drier conditions that accelerate forest mortality worldwide. Drought-induced tree mortality affects the forest ecosystem services and alters forest structure. However, our ability to predict the risk of mortality due to drought remains limited. Understanding how site and stand factors shape patterns of forest mortality is crucial for supporting forest management as well as creating appropriate adaptation strategies in the era of climate change. Until recently, many stand characteristics such as tree height, volume and stand density were measured by traditional field methods. However, the current use of remote sensing tools opens up new possibilities for forest monitoring and measurements. The aim of the analysis, was to indicate climate, site and stand characteristics determining the risk of stand level mortality during the period of sequential droughts in 2015–2020. Instead of sample-plot observations, we use wall-to-wall aiborne laser scanning and forest inventory data covering over 7 mln ha, from which milions trees were killed by drought. Spectral indices obtained from satellite imagery allowed additional assessment of the impact of drought on forest condition and mortality risk. We found that the occurrence of tree mortality is mainly driven by the lagged effect of the water deficit in the previous year expressed by the climatic water balance. Water deficit expressed by CWB is at the same time correlated with selected spectral indices. Spectral indices determined from satellite imagery combined with stand mortality risk determination and meteorological data can be used as an early detection system for the negative effects of drought. Models and maps obtained through unprecedented data availability indicate that the highest risk of drought-induced forest mortality occurs on the most productive sites and affects the oldest stands. Thus, the oldest and highly productive forests are most endangered by the projected climate change. Such exacerbated susceptibility to mortality should be considered in forest carbon sink projections, forest management, and policies designed to increase resilience and protect forest ecosystems

Comparing the Accuracy of Airborne Laser Scanning (ALS)- and Terrestrial Laser Scanning (TLS)-based methods, and manual measurements for short period Individual Tree Growth Detection

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Introduction: Accurate forest change studies require advanced methods for change detection and accurate reference data for determining the level of accuracy of the used methods. In this study, both topics were assessed. Three change detection methods (TLS-based, ALS-based and manual measurements) at individual tree level were cross-compared. Also, the accuracy of each individual datum and method was mathematically estimated based on the cross-comparison metrics.
Methods: A boreal forest test site in Evo, Finland was manually measured and laser scanned in 2014 and 2021. From the point clouds, tree stem curves were automatically extracted using the algorithm developed by Hyyppä *et al*. (2020). The growth in diameter at breast height (DBH) and stem volume was then calculated by a) subtracting the stem curve proportions of 2014 from 2021 in the TLS-based method, b) obtaining the stem curve of 2021 from the respective point cloud and then scaling the stem curve proportions according to height growth in the ALS-based method, and c) subtracting the manual measurements of stem proportions.
Additionally, the accuracy of each individual growth measurement method was calculated based on the RMSE and bias metrics of cross-comparison. Using these metrics, it was possible to derive a bias estimate and a standard deviation estimate of each individual growth measurement method.
Results: The results showed that the ALS-based method worked the best when growth manual measurements were used as reference data (correlation 0.44 {0.66}, RMSE 9.8 mm {0.052 m^3} in DBH {stem volume}). At short time periods, there is high correlation in the residual error of a scaled stem curve which was mostly cancelled when the scaled stem curve proportions were subtracted. This did not occur with the TLS-based method, in which the stem curve proportions were estimated individually for 2014 and 2021. However, because of under-canopy location and denser point clouds, the TLS-based single-time DBH and volume values correlated the best with the single-time manual measurements.
Because of two independent stem curve estimations, the TLS method produced the most outlying growth values (4 in DBH and 8 in stem volume). The ALS method produced 1 and 3 suspicious values of DBH and stem volume growth, respectively. The manual measurements produced only 1 suspicious value of DBH growth, but no suspicious stem volume growth values.
The standard deviation estimates of each individual method showed that the manual measurements are the most accurate (standard deviation 4 mm {0.03 m^3} in DBH {stem volume}), but the ALS-based method is closely followed (standard deviation 8 mm {0.04 m^3}).
Conclusion: The accuracy of laser-scanning based change detection methods is rapidly approaching the accuracy of the current, manually measured reference data. Therefore, in order to develop and benchmark even more advanced forest change detection methods, the accuracy of the underlying reference data should be considered.

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Towards Three Decades of Accurate, Sub-hectare Resolution Forest Biomass maps with Global DEM data and a Coarse Digital Terrain Model

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Introduction

Accurate, global, high-resolution maps of above-ground forest biomass density (AGBD) are needed for carbon accounting, forest resource management, and biodiversity research. Partly, these needs will be addressed by European Space Agency's BIOMASS satellite, expected to launch in late 2025. The eponymous objective of BIOMASS will be near-global, quasi-annual mapping of AGBD at 200 m resolution, for about five years. BIOMASS will use an innovative interferometric synthetic aperture radar (InSAR) sensor operating at P-band (wavelength: 67 cm) and capable of penetrating thick forest canopies. This will allow BIOMASS to see the biomass-rich tree trunks, also in the dense tropical rainforests, although the relatively coarse resolution, limited coverage, and short life-span of the BIOMASS mission will make it less suited for fine-scale forest monitoring applications. A by-product of BIOMASS will be the first near-global digital terrain model (DTM), with an expected best-case resolution of 100 m. In contrast to the AGBD estimates, which quickly become obsolete due to growth, deforestation, and forest degradation, topography under forests is usually stable in time and the DTM can remain valid for decades.

In this paper we propose and discuss a new pathway to near-global AGBD mapping, with the potential to provide accurate, 50 m resolution AGBD estimates for about three decades and using existing and forthcoming datasets.

Methods

The approach uses phase height (PH), which is the difference between a radar-based digital elevation model (DEM) and a DTM. PH is a height metric modulated by canopy density and as such, it has many similarities with mean canopy height from airborne laser scanning, a well-known proxy of AGBD. By subtracting the BIOMASS DTM from available DEM data from the SRTM (February 2000) and TanDEM-X (2010-late 2020s) missions, near-global maps of PH can be obtained at sub-hectare resolutions.

Results

Our results from eleven test sites on four continents indicate that PH derived from Copernicus DEM and a 100 m DTM has a consistent, near-linear relationship and strong correlation with AGBD. Moreover, the PH-to-AGBD scaling constant has smaller spatial variability than presented in literature. Furthermore, at 200 m resolution, the PH-based approach outperforms current AGBD estimates from spaceborne lidars and C- and L-band SARs.

Conclusions

We conclude that by using existing, global data from the SRTM and TanDEM-X missions together with the forthcoming BIOMASS DTM, unprecedented information on AGBD can be unveiled. The proposed approach can be used already now for AGBD mapping in areas with topography known from regional and national laser scanning campaigns (e.g., Netherlands, Spain, New Zealand). A clear advantage of the proposed approach, compared with many other approaches presented in the literature, is that it is simple and does not require technical knowledge typically needed to process raw TanDEM-X data. Nevertheless, further work is needed to validate the proposed method using accurate *in situ* data and develop an operational algorithm for AGBD mapping and monitoring.

Mapping and Modeling Commodity-driven Deforestation in South America

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Commodity expansion is a major driver of global deforestation. Removing deforestation from the supply chains of soft commodities has been gaining momentum in academia, non-government organizations as well as the private sector. In South America, soybean cultivation has been rapidly expanding over the past decades, often replacing natural vegetation, pasture, and other cropland. The objective of this study was to map deforestation driven by soybean expansion using historical and current satellite data and model future scenarios of soybean-driven deforestation using socioeconomic data and models.

We employed satellite data including Sentinel 2, Landsat and MODIS, probability sampling and field observations to generate 30 m resolution soybean maps over the South American continent from 2001 to 2024 (https://glad.earthengine.app/view/south-america-soybean). We combined the annual soybean map with annual global forest loss data of Hansen et al to map deforestation directly and indirectly driven by soybean expansion. We integrated the satellite-based land use maps with survival analysis and geo-economic gravity model to establish connections between the global market and local land use responses. We conducted a scenario-based analysis and projected the future spatial distributions of soybean cultivation in Brazil under the Shared Socioeconomic Pathways.

Soybean expansion was found in all major biomes including the Brazilian Amazon, Atlantic Forests, Cerrado, Chaco, Chiquitania and Pantanal. Across the continent, 9% of forest loss was converted to soybean between 2001 and 2016. Soybean-driven deforestation was concentrated at the active frontiers, nearly half located in the Brazilian Cerrado. Soybean will continue to expand due to persistent global demand. Continued satellite monitoring and implementation of environmental policies are required to decouple soybean production from natural vegetation loss.

Global Vegetation Monitoring in near Real-time

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Forest disturbance alert systems enable low latency monitoring of forest loss, supporting forest management activities and enforcement. We have been monitoring forest loss pan-tropically in near real-time using Landsat satellite data with the system GLAD-L since 2017, and across the Amazon basin using Sentinel-2 data since 2020. Expanding from tropical to global, our most recent alert system, DIST-ALERT, flags all vegetation cover loss relative to its seasonal near-term historical range using Harmonized Landsat Sentinel-2 (HLS) data. With a revisit rate of 2-4 days, this freely available 30 m dataset is uniquely suited for near-real-time monitoring. The fractional vegetation cover is mapped using a K-Nearest Neighbors model trained with vegetation cover percent estimates derived from 8 cm multispectral drone data collected across numerous biomes. The vegetation cover is estimated for each new observation and compared to the minimum cover estimate from all observations in a seasonal window of ±15 days in the previous three years. Observations with anomalously low fractional vegetation cover are flagged as disturbance and monitored through subsequent observations to track duration and build or decrease confidence. All of the high confidence disturbance alerts throughout the calendar year are summarized to an annual product. When combined with an ancillary forest mask, this new system allows users to monitor forest loss events far beyond the tropics and in both seasonal and evergreen forests. Together these systems provide high cadence disturbance alerts to support enforcement of conservation policy, aid land managers, and facilitate downstream science.

Predicting changes in stream temperatures using LiDAR-derived simulations associated with harvesting of forest buffers

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Riparian zones are the corridor of vegetation between a stream network and the upland forest. Sustainable forest management of riparian zones is essential to maintaining the key ecosystem services they provide to stream systems and mitigating potentially harmful effects of forest harvesting on stream processes. Riparian buffers are the primary tool used to protect stream habitat for anadromous salmonids, which are ecologically, economically, and culturally important keystone species in North America. In British Columbia, Canada, riparian buffers consist of a nested harvesting/retention scheme, in which a total Riparian Management Area (RMA) can have varying levels of harvesting, from partial thinning to a clearcut.
Critically, riparian buffers provide shade to a stream by attenuating solar insolation and therefore regulating temperature, as insolation at the stream surface is the primary driver of stream thermal regimes. Harvesting of near-stream vegetation and removal of stream shading can increase stream temperatures by more than 10° C, raising stream temperatures to levels potentially lethal for salmon and other aquatic species. Changes in climate have the potential to directly contribute to warming stream temperatures and drought conditions in watersheds, thereby emphasizing the importance of the management of riparian buffers.
While light detection and ranging (LiDAR) data from Remotely Piloted Aircraft Systems (RPAS) have previously been utilized to create models of insolation and shading from canopy height models (CHMs), few studies have linked these models to stream temperatures. To determine the effects of different management strategies, we also used solar insolation models with simulations of varying forest harvesting intensities to estimate the increase in stream temperature associated with removal of riparian forest stands.
RPAS data were acquired over five stream segments in a watershed on Vancouver Island, Canada. The resulting CHMs were used to create insolation models, which in turn were used as an explanatory variable in a quadratic regression with water temperature as the response variable. Models revealed that solar insolation modeled from RPAS point clouds explained up to 90% of the variation in stream temperature.
Harvesting simulations were created by using an individual tree detection (ITD) algorithm to identify tree crowns and remove a certain percentage of trees (25% and 50%, respectively) from the CHM. These “thinned” CHMs were then added to a bare-earth digital elevation model (DEM) and input to the insolation model. A full bare-earth DEM was used to simulate a complete harvest of the RMA. The regressions were then used to generate predictions of stream temperatures using these simulated insolation values as the explanatory variables.
Simulations of riparian forest thinning predicted an increase in stream temperatures by an average of 1°C, with clearcutting of the RMA corresponding to a predicted increase of approximately 6°C. While harvesting of streamside stands is known to increase stream temperatures, RPAS-acquired LiDAR data can be used to gauge the potential impact of riparian forest harvesting on stream temperatures at high spatial resolutions before forest operations begin. These predictions could be crucial to preserving the populations of aquatic species such as salmonids in the face of a changing climate.

Assessing uncertainties in Surveys of Forest Resources applying Model-based Inference

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Model-based inference is attracting increasing interest among scientists and practitioners involved in large-area assessment of forest resources based on remotely sensed data. However, whereas it is straightforward to estimate and apply a model for, e.g., biomass prediction to all map units across an area of interest, it is far from trivial to assess the uncertainties that arise in such surveys. In this presentation, we first contrast model-based inference with design-based inference, and discuss what implicit assumptions are made when these modes of inference are applied. We further show that model-based predictors at the level of map units are typically model-unbiased, although in the same time they are typically design-biased, and sometimes severely so (e.g., Ståhl et al. 2024). The standard result that small true values are overestimated and large true values underestimated in surveys based on remotely sensed data follows from adopting a design-based perspective when the performance of model-based predictors are evaluated. Thus, it is important to distinguish clearly between the two concepts of inference.
The second part of the presentation addresses a decomposition of an important measure of overall uncertainty in surveys relying on either model-based or design-based inference, i.e. the mean square error (MSE). For predictors in model-based inference (such as predictors of aboveground biomass density), we show that the MSE comprises four components: the variance of the predictor, the variance of the true value being predicted (which is a random variable in model-based inference), the covariance between the predictor and the true value, and the squared model-bias. Based on remotely sensed and field data mimicking conditions in Western USA and East Africa, we applied Monte Carlo simulation to assess the magnitudes of the MSE components in different forest survey contexts. For example, during the presentation we will show results demonstrating the risk of underestimating the MSE if models are applied to forest conditions that differ from those where they were trained.

Ståhl, G., Gobakken, T., Saarela, S., Persson, H. J., Ekström, M., Healey, S. P., ... & McRoberts, R. E. (2024). Why ecosystem characteristics predicted from remotely sensed data are unbiased and biased at the same time–and how this affects applications. *Forest Ecosystems*, *11*, 100164.

Effects of forest management on the microclimatic buffering in boreal forests

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The majority of Fennoscandian boreal forests are managed. Traditionally, forest management has been based on even-aged rotation forestry, characterized by periodic clear-cut harvests. On the other hand, uneven-aged management, or continuous cover forestry, has recently emerged as an alternative that may lead to more diverse and resilient forests. Forest management inherently changes the physical structure of forests, affecting not only the carbon storage but also light regimes, local temperature and humidity variability (i.e. microclimate), and thus habitat availability inside forests, which all contribute to the regulation of ecosystem functioning, services, and biodiversity. Yet, the effects of management on microclimate, which is one of the key drivers of local biodiversity patterns, has not been comprehensively studied.

In this study, our goal was to increase the understanding of the effect of forest management on the large-scale temperature (macroclimate) buffering capacity of boreal forests. First, we quantified fine-scale structural differences between uneven-aged and even-aged forests. Next, we investigated how these structural characteristics affect the temperature buffering capacity of forests and what are their spatiotemporal microclimate dynamics. In the final step, we upscaled the analysis over the whole of Finland to estimate the area of forests where temperature buffering has not reached its maximum. To achieve these goals, we used both field measurements and modelling approaches. Our study area in Southern Finland represents both uneven-aged forest stands as well as even-aged stands of various age categories. We used terrestrial laser scanning for assessing the structural differences between management types, and microclimate measurements to estimate the temperature buffering capacity. Finally, we used almost 800 microclimate loggers located in different forests across Finland to train a machine-learning model for spatializing the analysis over Finnish forests. As an input, we use the Multi-Source National Forest Inventory data from the year 2021, which includes management-related variables such as forest age, canopy cover and tree height.

The results show that although different management types result in similar patterns in total plant material, they differ significantly on its vertical distribution. This vertical allocation of plant material was also found to be an important determinant of temperature buffering capacity: increasing canopy layers and the density of the understory led on average to more buffered temperature variability compared to clear-cuts and forests with fewer layers. Our results highlight the dynamic nature of even-aged forests, where the structural characteristics and buffering capacity change drastically with the rotation, whereas uneven-aged forest structures and microclimate remain more stable over time. Since the buffering capacity is highly dependent on stand age and Finnish forests have become younger, we hypothesize that the machine-learning model will reveal a significant number of forest area where the temperature buffering has not reached its maximum. We expect our results to increase the understanding of the impacts of forest management practices on forest microclimates and consequently their ecological functions, shedding light to a less considered aspect in the ongoing forest discussions.

Automatic Detection of Red Needle Cast Outbreaks in Radiata Pine Plantations in New Zealand using Multi-scene, Multi-temporal Satellite Imagery

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Red needle cast (RNC), caused primarily by the oomycete pathogen, *Phytophthora pluvialis*, has quickly emerged as a significant foliar disease affecting radiata pine (*Pinus radiata* D. Don) in Aotearoa New Zealand. Symptoms of the disease typically appear on the lower branches of infected individuals, rapidly spreading upwards through the canopy turning the needles red which are eventually shed from the tree. Research by Scion at heavily infected sites has shown RNC to reduce stem basal area growth by approximately 35% in the year following disease. Radiata pine comprises approximately 90% of the plantation forest estate throughout the country, hence the disease poses a considerable biological and financial threat to the resource. Therefore, the development of a method to accurately detect and monitor the spread of this disease over large areas has become increasingly important.

This study presents a framework for using very high resolution (VHR) satellite imagery to automatically map and monitor outbreaks of RNC in planted radiata pine forests. This methodology was tested on five WorldView satellite scenes collected over two study sites within the Gisborne Region of New Zealand's North Island. Each scene was acquired in September across a timespan of five years. Four scenes were acquired yearly (2018 - 2020 and 2022) for Wharerata, while one additional scene was obtained in 2019 for Tauwhareparae. Training areas selected for each scene were manually delineated, combined with pixel-thresholding rules inferred by normalised difference vegetation index values (selected empirically) to produce 'pure' training pixels for each class. A leave-one-scene-out, pixel-based, random forest classification approach (RF-LOSO) was developed and used to classify all images into three distinct classes: healthy pine forest, unhealthy pine forest, and background.

The overall accuracy of the models on the internal validation dataset ranged from 92.1% to 93.6%, while overall accuracies calculated for the left-out scenes ranged from 76.3% to 91.1% (mean overall accuracy of 83.8%). The user's and producer's accuracies across the three classes were 60.2 – 99.0%, and 54.4 – 100%, respectively. The results from this study demonstrate the potential of using a random forest classifier trained on a set of satellite scenes for the classification of healthy and unhealthy pine forest in new and independent scenes. The framework developed here paves the way for a scalable and largely autonomous forest health monitoring system based on the annual acquisition of VHR satellite imagery at the time of peak disease expression. This approach will reduce the need for manual interpretation and delineation.

Airborne Laser scanning application in Operational Forestry in Poland

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LiDAR technology makes it possible to accurately determine the biometric characteristics of trees as well as many stand variables. Airborne laser scanning has been used for more than 20 years to determine forest characteristics, whether based on the detection of individual trees or an area-based approach.
In Poland, work has been ongoing for almost 20 years to integrate airborne laser scanning data into practical forest management, which is carried out every 10 years. In recent years, it has been possible to develop and practically test a method for estimating growing stock volume (GSV) at the stand level using ALS data and permanent sample plots. This method is currently being implemented in forestry practice and is to be approved as an alternative in the preparation of forest management plans in state forests.
The presentation, will demonstrate the process of implementing ALS solutions in forestry practice using a dedicated ALSgator application. The application consists of two modules - the control module and the stand variable prediction module. Within the control module it is possible to check many parameters of the ordered point cloud and the aerial orthophoto and to check whether the data meet the requirements. The stand characteristics estimation module allows the determination of the following stand level characteristics: GSV, basal area of all trees, DBH of all trees, DBH of the 100 thickest trees per hectare, the number of trees per hectare, the top height of the 100 thickest trees per hectare, the average height of all trees, the average height of the first layer trees.
Furthermore, we will present the experiences and challenges in the practical application of ALS from the perspective of the Polish forestry sector.

Precision forestry – Current status of Practical Implementation and Research problems

Prof Krzysztof Stereńczak[1,2,3], Martin Mokros[3,4], Carlos Cabo[5], Marcus Hollaus[3,6], Juan Suarez[7]
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Remote sensing has revolutionized the way we monitor and analyze forested areas, offering a new vantage point through advancements in technology. The emergence of laser scanning technology, particularly in the early 2000s, has enabled a more precise and automated approach to detailing the biometric characteristics of individual trees, surpassing the capabilities of earlier methods.
Currently, the market offers a variety of laser scanning technologies ranging from ground-based systems to those deployed on aircraft and satellites. Among these, Airborne Laser Scanning (ALS) stands out as the most seasoned technology, with several decades of application behind it. ALS allows for the identification of individual trees and the characterization of forest stands and ecosystems based on their traits. There is also a broad array of ground-based technologies, including mobile laser scanners (MLS), an assortment of personal laser scanners (PLS), and UAV Scanners (ULS). These technologies provide significantly improved spatial and temporal resolution, facilitating detailed assessments of tree structure, branching patterns, architecture, species identification, and dynamic changes over time.
Laser scanning is thus employed across various fields, from urban forestry to productive forestry and forest ecology, supporting tasks ranging from the characterization of city trees to global forest biomass mapping (e.g., GEDI). It serves different scales of analysis, including individual forestry operations, state-wide forests, and international forest ecosystem research. This presentation will showcase current examples of precision forestry using laser scanning, offering a structured review of its practical applications, limitations, and a look into ongoing research challenges and anticipated future developments.

Automatic Detection and Mapping of Lying Deadwood in Nature Reserve Lipowka (Niepolomice Primeval Forest, Poland) using dense ALS point clouds and AI laslogic approach in LAStools (rapidlasso).

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Introduction/Aim:

The role of dead wood in tree stands cannot be overestimated, as it plays a very important role in increasing biodiversity indicators, being the habitat of many species. Moreover, dead wood is an extremely important link in the circulation of matter in the forest ecosystem, increasing of water retention, maintaining soil moisture. In most cases, it is a great solution of CO_2 sequestration and carbon accumulation, although climate changes may reverse this. The accumulation of large amounts of dead wood caused by drought, hurricane winds, insect outbreaks etc. can lead to an increased risk of forest fires and thus the release of large amounts of $C0_2$ and habitat degradation. Dead wood mapping methods can be supported by photogrammetry techniques (especially in the case of open post-hurricane areas) and LiDAR as well. Modern ALS or ULS technologies are able to provide very dense point clouds, which, using advanced AI techniques, open up new possibilities for lying dead wood inventory. The test site Nature Reserve “Lipowka” in Niepolomice Primeval Forest (25,7 ha) established in 1954, is located in southern Poland is covered by natural old-growth oak-hornbeam forests (oak, hornbeam and lime: age 190 years, DBH 89 cm, H 33.0 m, growing-stock volume 581 m3/ha).

Methods:

Specially designed ALS LiDAR campaign (RIEGL VQ780i; 18 strips; overlap > 50%, cross-flights) carried out during the LEAF-OFF period were used for the research. The density of the ALS point cloud was approximately 120 pts/m2 (ground) and 560 pts/m2 (all classes). Detection of dead wood lying in the Lipowka reserve was carried out using the rules of the AI laslogic tool (rapidlasso GmBH). They made it possible to define objects (tree logs) and recognize them in a dense cloud of points. Those tree logs that deviate from the definition can also be recognized using fuzzy logic, with the rules being optimized by the AI system and, if necessary, modified with user participation. The set of rules can also be used to classify objects. The use of fuzzy logic allows the categorization of trees into fixed groups comparable to classes, without, for example, specifying exact height limits. Trees higher than the maximum set height are also taken into account and assigned to the set of standing trees. The evaluation of the created AI algorithms was made based on the number of correctly recognized tree logs and their fragments in relation to the reference data, which were classified tree trunks vectorized in the ALS point cloud and on a specially selected 1 ha area of the MHLS point cloud (ZEB Horizon). The algorithm also analyzes the directions of tree fall, which may provide an answer to the wind directions or the gravity of tree crowns to the gaps in the tree canopy that appear after the fall of the dominant trees.

Conclusion:

Automation of biometric measurements of dead trees, as well as their spatial mapping can provide contemporary foresters with important information regarding the history of forests and the dynamics of processes occurring in the past.

321

Inferences on the Nitrogen Cycle: Coupled Isotopic and Hyperspectral approaches to assess Forest Retention and Responses to Nitrogen additions

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Human alterations to the global nitrogen (N) cycle have dramatically increased both acute (e.g., fertilization) and chronic (e.g., atmospheric deposition) rates of N input into terrestrial environments. Forest ecosystem retention of this added N has important implications on terrestrial productivity and adjacent aquatic ecosystem health. Traditionally, site-specific, labor-intensive, mass balance approaches have been required to quantify ecosystem N retention or loss, but recent evidence suggest the potential use of N stable isotope signatures ($\delta^{15}N$) as integrative indicators of the degree of openness or closedness of the N cycle in forests. Here we discuss the potential of using hyperspectral remote sensing to assess foliar $\delta^{15}N$ as a static assessment of historical N cycling rates and using those inferences to predict future forest ecosystem responses to added N across the managed forests of the southeastern (loblolly pine) and Pacific Northwest (Douglas-fir) Unites States as well as New Zealand (radiata pine).

207

Creation of a Digital Twin of the Forest of Dean in South England for precision forestry applications

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Digital Twins (DT) are virtual representations of physical objects, systems, or processes, designed to simulate, analyse, and predict their behaviours in the real world. These digital models are created using data collected from sensors and other sources, which can include real-time data, to mirror the physical counterpart as closely as possible. This allows for in-depth analysis, monitoring, and optimization of performance, as well as the ability to test scenarios and solutions in a virtual environment before applying them in reality.
The application of DF to forestry involves creating a virtual model of a forest that can simulate its physical characteristics, processes, and dynamics. This model can be updated in real time or at regular intervals with data from various sources, including satellite imagery, drones, ground sensors, and manual surveys.
A DT has been created for a forest district in South England. The Forest of Dean stands are characterised by a complex structure with a mix of species and ages on a progression to natural forests. As a result, current stand models are very limited to forecast production, test different management alternatives or gauge the impact of disturbances. The aggregated nature of the baseline data embedded in the Forestry England Subcompartment Database incorporates considerable uncertainty in any model predictions. Therefore, better alternatives have been sought by realigning the subject of all the analysis to individual trees.
Tree lists have been created using a combination of Airborne LiDAR (ALS) and high-resolution satellite imagery such as Planescope. Whereas trees are being delineated using normalised pointclouds, species labelling has been achieved using time-series of satellite imagery that looks at the particular phenological cycles for each vegetation type. Mobile Laserscanning has been captured in plots of 30x30 m to calibrate allometric relationships to define stem properties, which cannot be seen directly from ALS. The reconstruction of stem profiles is being done using 3DFin, developed by the University of Oviedo and CETEMAS in Spain. This application also creates a tree list with height and DBH. As pointclouds were registered to the OSGB National Grid, then DBH extracted from the ground could be added seamlessly to tree lists generated to the tree lists created by ALS. As a result, allometric models were created to link species, tree height, canopy width, depth and volume to DBH. So, it was possible to upscale the estimations of DBH to all the area being covered by ALS, totally 80 km^2.
The final tree list has been used as baseline data to run production forecast models and calculating the probability of wind damage using ForestGALES. Different management options such as clearfelling, thinning intensities, or transitions to Continuous Cover Forestry have been tested to evaluate the long-term effects on timber production, changes in the probability of wind damage or the recruitment intensity for natural regeneration.
This presentation will show examples of the advantages of using precision forestry methods for implementing the best possible alternatives in terms of adding volume increments and minimising the risk of wind damage.

Multi-temporal 3D virtual forest reconstruction using terrestrial laser scanning in a temperate forest

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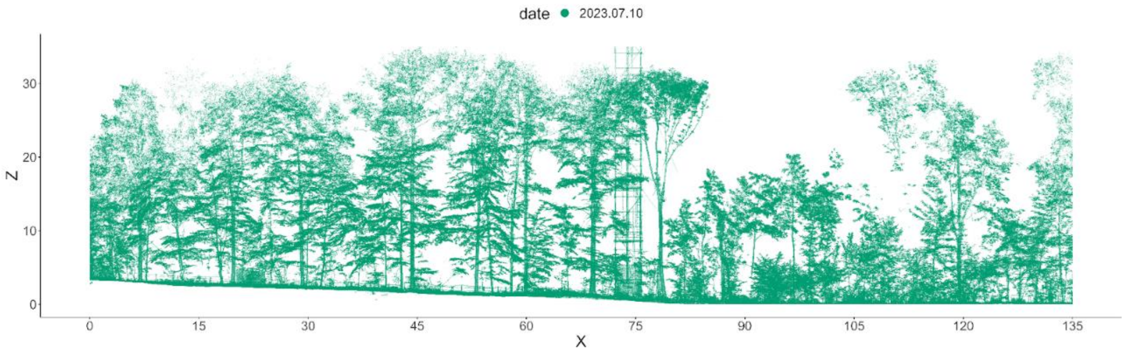
Introduction:

European forests are currently undergoing large-scale changes in both structure and species composition, primarily driven by climate change, and various disturbances affecting the forest canopy. The canopies of forests across Europe are currently opening up due to tree mortality caused by factors such as drought, pests, storms, and fire. Understanding the implications of these changes for forest functionality is crucial for effective forest management. Therefore, it is essential to accurately quantify the spatial and temporal relationships among forest structure, light availability, and microclimate.

Methods:

To address this need, we have established a novel edge-to-core transect within a temperate deciduous forest near Ghent (Aelmoeseneiebos, Gontrode, Belgium). This 30m-wide transect spans from the forest edge to 135 meters deep into the forest interior, encompassing both an oak-beech-dominated zone and an ash-dominated zone characterized by ash dieback. Along the transect, we have deployed a densely spaced network of light and microclimate sensors at 15-meter intervals. Additionally, a fiber optic sensing cable for distributed temperature sensing (both in air and soil) runs along the entire transect. A 35-meter-high measuring tower is part of the setup, allowing for measurements of light and microclimate along a vertical transect from the ground till above the canopy. To quantify the temporal and spatial variations in forest structure, we have collected terrestrial laser scanning (TLS) data on a monthly basis, since March 2023. This data is acquired using a RIEGL VZ400i laser scanner at a pulse repetition rate of 600 kHz using a 15 by 15 m grid. Using this multi-temporal TLS data we will reconstruct a 3D virtual forest transect throughout time.



To construct this 3D virtual forest transect, the transect point cloud is first fully segmented to individual tree point clouds in RIEGL's RiSCAN PRO software using a combination of the software's tree segmentation plug-in and manual corrections. Next, the tree point clouds undergo a leaf-wood separation using the GBSeparation algorithm of Tian et al. (2022). This is followed by reconstructing the woody points to the finest detail using cylinders (so called QSMs, quantitative structure models) for each individual tree applying the treeQSM version 2.0 workflow of Calders et al. (2015) which builds upon Raumonen et al. (2013). Leaves are added to the tree QSM structures using the Foliage and Needles Naïve Insertion (FaNNI) algorithm (Åkerblom et al., 218).

Outlook:

This virtual forest transect will serve as input for radiative transfer modeling (RTM), a simulation method that simulates the interaction between light and forest structure. Utilizing highly detailed forest structure obtained from TLS data, 3D RTMs provide an effective means to accurately model light transmission within forests at a high resolution. Using this approach we aim to (i) validate 3D light measurements conducted along the transect and (ii) implement virtual light sensors. The former enables the assessment of uncertainty in the collected time series data, while the latter offers a comprehensive understanding of the light conditions in the canopy. This information is crucial for evaluating the impact of canopy structure on light penetration and its subsequent effects on the microclimate.

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Exploration of Coastal Degradation in the Eastern United States

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Degradation of coastal ecosystems is of increasing concern due to sea level rise, salt water intrusion, storm events, land management decisions, and other factors. Areas of vegetation stress and reduced productivity can be observed from multispectral imagery and multitemporal lidar. We examine the eastern coast of the United States from New Jersey to southern Georgia within forests, agriculture, and marshland areas. For a pilot area in the Delmarva Peninsula (Delaware, Maryland, and Virginia) we conducted a preliminary high-resolution analysis with multitemporal lidar from 2010 and 2015 combined with PlanetScope data from spring and fall 2022. Exploratory machine learning CART classification demonstrated the ability to separate degraded and healthy vegetated areas with an overall accuracy of 93% and 5 tree splits for 43 samples, with the red edge band, blue band and height metrics being the deciding predictors. The largest confusion in the classification was between degraded forest versus ghost forest. At the regional scale, classification analysis is driven by the 10m Sentinel-2 bands from April and September 2022, 10 m ESA 2020 World Cover product, and the 10 m ETH Global Sentinel-2 Canopy Height product. Preliminary results from machine learning classification (random forest model with 50-fold cross validation) showed an overall accuracy 83%, respectively with 801 samples derived from manual interpretation of high-resolution imagery and some field visits, with a class accuracy of 85% for total degraded forests, but significant confusion between ghost forests and other degraded forests. We also examined the Landsat time series data from 2000-present using the Continuous Change Detection and Classification (CCDC) algorithm for selected degraded versus healthy forested sites. For degraded forests, we see some evidence of decline in NDVI and tasseled-cap greenness over time prior to disturbance that is not evident in nearby healthy forest sites. Our results highlight the value of incorporating lidar-derived vegetation height and ground elevation into multitemporal/multispectral classification of coastal degradation.

Assessment of Forest Nitrogen Dynamics with Multitemporal Remote Sensing

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Nitrogen is an important nutrient for the growth and productivity of forest. Foliar nitrogen and nutrient deficiencies have been successfully quantified with remote sensing for many systems. However, remote sensing assessments of the rates of nitrogen movement within and through forest systems has been historically constrained by a lack of necessary data at appropriate scales. We have now moved into an era where multitemporal remote sensing data are available in locations coincident with long term field experiments. Here, we explore the use of multitemporal Landsat data to characterize nitrogen dynamics of 10 pine stands across New Zealand that underwent a fertilization experiment described in Davis et al. (2012). We used the Continuous Change Detection and Classification (CCDC) of landcover algorithm to fit all available Landsat data from 2000-2012, which included stand establishment and growth through the historic fertilization experiment. We used the difference of nitrate-N between control and fertilization plots (from Davis et al. 2012) to rank the leaching across the sites.CCDC results suggest that wetness and NDVI fit parameters may be indicative of relative leaching potential. The site with the lowest leaching had more than double the mean and amplitude of fit to the wetness index in the years following the fertilization experiment (mean=-0.005, amplitude=0.025 in 2010 for the site with the lowest leaching, versus mean=-0.025, amplitude=0.01 in 2010 for the site with the highest leaching). Our analysis highlights the value of multitemporal remote sensing analysis to explore stand development and nitrogen dynamics.

Remote Sensing-based Aboveground Biomass Yield Curves for Dominant Boreal Tree species

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Introduction/Aim:
Forest aboveground biomass (AGB) is a crucial parameter for carbon storage, forest function, and habitat assessment. Accurate knowledge of current AGB and its dynamics is essential for sustainable forest management and carbon monitoring. Common methods for estimating AGB, such as permanent sample plots, yield curves, or simulations, often lack spatial and forest structural representation. To address these limitations, we present an integrated model-driven, data-informed approach for developing AGB yield curves exclusively from remote sensing data.

Methods:
Our approach leverages Landsat time series data of annual AGB values, tree species composition, and age. We applied this methodology to a 76.5 million-hectare study area in Alberta, Canada, encompassing diverse forest conditions, species, and ages, partitioned into 34 150×150-km analysis tiles to account for local variation. The 37-year AGB time series (1984–2021) were filtered to create a representative and noise-reduced sample set for developing remote sensing-derived AGB yield curves. Using a nonlinear mixed-effects modeling framework, we generated 127 models for eight tree species across the study area. The development process included filtering steps to address uncertainties in pixel-level AGB estimates and to ensure the use of best-available data.

Results:
Developed yield curves offered insights into AGB dynamics across different forest types and conditions. The performance of the models was evaluated using three independent datasets: permanent sample plots, existing yield curves, and an established growth and yield simulator. Model assessment showed the influence of geographic position and tree species representation in the reference data. In general, the models tended to underestimate AGB and AGB increment, with relative RMSE ranging between 22.66% and 70.30% for permanent sample plots. Despite these challenges, the large number of available time series of AGB allowed for the development of models for less abundant species that are often grouped into broader species groups when traditional methods are used.

Conclusion:
Our findings confirm the feasibility of developing AGB yield curves exclusively from remotely sensed data, covering a wide range of species and stand structural conditions representing a large spatial extent. The methodology developed provides insights into the use of Landsat time-series data for yield curve development, emphasizing the importance of modeling, data filtering, and recognition of the challenges of model assessment. The results serve as a foundation for future research and the practical application of remotely sensed data in various aspects of sustainable forest management, carbon monitoring, and growth and yield modeling. Additionally, these models have the potential to create large-area maps of historical forest growth and to map projected future biomass values.

Mapping of Forest Structural Patterns by GEDI, Sentinel-1 and 2

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Introduction/Aim:
Forest ecosystems are complex, varying both spatially and vertically. Understanding Forest Structural Patterns (FSP) is crucial for estimating forest biodiversity and habitat suitability, as well as managing plantation and secondary forests. While satellite remote sensing techniques can map basic forest environment aspects such as vegetation coverage and canopy heights from space, comprehensive FSP mapping remains a challenge. Recent advances use foliage height diversity as a measure to quantify complex vertical characteristics of forests, but FSPs are often overlooked.
To address this, we developed a new technique for clustering FSPs.

Methods:
Global Ecosystem Dynamics Investigation (GEDI) L2A product was used. We treated the foliage vertical profile, calculated from relative height measurements, as unidirectional data and applied it to dynamic time warping (DTW) that is a widely used method for aligning sequences. We used the calculated DTW distances to measure the similarity of the foliage vertical profiles. These DTW distances allowed us to classify the profiles using a k-Medoids unsupervised classification.
We grouped all FVPs from GEDI observation points into three clusters: *Tall crown-rich pattern, midstory-rich pattern*, and *understory-rich pattern*. These clusters were then spatially estimated using a Random Forest classifier from Sentinel-1 (VV and VH) and -2 (Band 1-12 and enhanced vegetation index: EVI) variables. We demonstrated this technique in Nikko-city, Japan, where a comprehensive tree species dataset is publicly available.

Results:
We mapped the FSP at the spatial resolution of 10 m in the study area. The pattern does not correspond to that of species distribution, indicating that the FSP may represent the different aspect of forest ecosystem. The results revealed interesting characteristics hidden in the vegetation cover or canopy heights, providing a new insight of monitoring forest ecosystem.

Conclusion:
The forest structural patterns map has a potential to be a planetary variable to represent an aspect of forest ecosystem. As our approach only uses satellite-based observation data (lidar, SAR, and optical) and doesn't require costly manual measurements, it can be extended for large-scale mapping in future works.

Using Remote Sensing to assess Field Margin Trees and their Implications for Wild Biodiversity in an Agricultural Landscape

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As global biodiversity is in decline, farmland agroecosystems present a pivotal opportunity for improving landscapes for conservation and transitioning towards a more efficient food production system that is more aligned with natural resource availability. Field margin trees including hedgerows, tree lines, and forest fragments present potential habitat and corridors for wild biodiversity. There is no existing spatial record of the existing field margin trees in Canterbury Plains, New Zealand. Canterbury Plains is a highly productive agricultural landscape situated with the Southern Alps to the west and Banks Peninsula to the east, both areas with high levels of native biodiversity. It is therefore realistic that field margin trees would function as corridors between the two places.

The use of remote sensing to map field margin vegetation has recently gained popularity globally, but is novel to New Zealand. In this study, object-based image analysis (OBIA) will be used to identify and map field margin trees in Canterbury Plains, New Zealand. OBIA will be performed using aerial imagery and lidar data, and field margin vegetation will be classified with a random forest classifier.

The anticipated results are a detailed map and data layer of the field margin trees in Canterbury Plains including whether the fragments or hedges are composed of native or non-native tree species, and a workflow to be scaled or applied to the rest of New Zealand's agricultural landscapes or trees in human dominated landscapes elsewhere. The map will also be coupled with data from mammal, insect, and avian data from an ecology study that I conducted in February 2024 surveying wildlife use of field margin trees as habitat in Canterbury Plains. The gained remote sensing knowledge on field margin tree extent combined with ecological information on how wildlife is using the space will be used to inform regenerative agriculture and conservation programs in the region, with implications for the ecosystem services of trees in farmland worldwide.

Modeling the Effect of Stand and Site characteristics on the probability of Mistletoe Infestation in Scots Pine Stands using Remote Sensing Data

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Over the past decade, there has been a marked increase in the presence of mistletoe (*Viscum album* ssp. *austriacum*) within Scots pine (*Pinus sylvestris*) stands in several European regions, resulting in significant disturbances. Given the potential implications for forest health and management, understanding the factors influencing the occurrence of mistletoe in these stands is crucial for the implementation of effective forest management strategies aimed at mitigating damage and preventing future spread of mistletoe. Today, remote sensing is a reliable source of information in forestry and the use of different methods is constantly evolving. High spectral resolution imagery is provided by multi- and hyperspectral sensors mounted on satellites, aircraft or unmanned aerial vehicles (UAVs) such as drones. UAVs provide higher spatial resolution than satellite imagery and ensure high labour productivity. With high spatial resolution drone data, we can obtain accurate information on the location and extent of mistletoe in stands. However, Airborne Laser Scanning (ALS) measurements allow us to obtain highly accurate data on stand characteristics at an unprecedented scale. Consequently, the range of variation in growth conditions can be greatly expanded with ALS measurements. Therefore, the fusion of ALS and UAVs is a reasonable alternative to traditional inventory methods, which are time consuming, costly and can be subject to large errors. Therefore, the main objective of this study was to determine the probability of mistletoe occurrence in Scots pine stands in relation to stand related endogenous factors such as top height and stand density, as well as topographic and edaphic factors. We used unmanned aerial vehicle (UAV) imagery of 2247 stands to detect mistletoe in Scots pine stands, while most stand and site characteristics were calculated from airborne laser scanning (ALS) data. We found that mistletoe infestation in Scots pine stands is influenced by stand and site characteristics. We documented that the densest and tallest stands were more susceptible to mistletoe infestation. Site type and specific microsite conditions related to topography were also important factors influencing mistletoe occurrence. In addition, climatic water balance (CWB) was a significant factor in increasing the probability of mistletoe occurrence, which is important in the context of predicted temperature increases associated with climate change. Our results are important for better understanding patterns of mistletoe infestation and ecosystem functioning under climate change. In an era of climate change and technological development, the use of remote sensing methods to determine the risk of mistletoe infestation can be a very useful tool for managing forest ecosystems to maintain forest sustainability and prevent forest disturbance.

Quantifying the extent and drivers of global forest loss with high-resolution satellite data

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The project aims to improve the quantification of global forest loss extent and drivers by utilizing high-resolution satellite data. Specifically, we have acquired circa 3m resolution PlanetScope data and 10m Sentinel-2 data for a global sample of 600 5x5km blocks for the year 2018 (baseline year). We have mapped each block using the combined stack of PlanetScope and Sentinel-2 data for the baseline year to identify the areas of tree cover loss using automated classification (decision trees classifier). Based on the imagery directly following the disturbance we have visually attributed each mapped tree cover loss pixel within each block to the initial disturbance type, including mechanical forest clearing (manual vs. mechanized), natural disturbances (insects, floods, hurricanes, windfalls), fires and flooding due to dam construction. Using imagery (PlanetScope basemaps and Google Earth) for the next three years after the disturbance (2019 - 2021), we have assigned a proximate cause (driver) of forest loss (Geist and Lambin 2002), including the following categories: conversion of forests to other land uses (pasture, cropland, tree plantations, construction, mining), forestry operations in natural forests (clearcuts with natural regeneration vs. planted, selective logging), forest rotation in shifting cultivation, tree plantation management (timber and non-timber plantations), natural disturbances, and wildfires (excluding conversion to other land uses by fire). This sample-based study will also contribute to an improved understanding of the quality of the state-of-the-art global forest loss map (Hansen et al., 2013), which is a key dataset of the Global Forest Watch platform.

The preliminary estimate of global tree cover loss based on all 600 sample blocks is 26,8 Mha ± 2,2 Mha (SE 8.1% of the estimate). The map-based (pixel counts) estimate of forest loss area from the global map (Hansen et al., 2013), is 30,2 Mha, which is higher than the sample-based estimate, but still within the sample-based estimate’s 95% interval (22.5 – 31.0 Mha). We will present a detailed comparison of our sample-based estimate with the global map, including attribution of the sources of errors for the sample blocks where the map and the sample disagree (e.g., difference in mapping resolution, timing of loss events).

Of the total forest loss area estimated from the sample, the major initial forest loss types are mechanical mechanized forest clearing (62.0 ± 4.0%), mechanical manual clearing (24.9 ± 3.2%), and fires (9.4 ± 2.1%), with natural disturbances contributing less than 2% each and 3.6% ± 1.5% combined and flooding due to dam construction 0.04 ± 0.03%. In terms of the proximate causes of forest loss, 31.9 ± 3.7% was due to conversion to other land uses, 23.5 ± 5.0% due to tree plantation rotation, 17.8 ± 2.7% due to tree cover rotation in the shifting cultivation cycle, 13.8 ± 2.8% due to forestry in natural forests, 9.3 ± 2.1% due to wildfires and 3.6% ± 1.5% due to natural disturbances. Despite the limited sample size of the study, we are planning to report estimates of driver proportions for major forest loss driver groups within continents and climate domains.

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Measuring Mangrove Surface Elevation Change with your Phone

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Introduction/Aim: The resilience of coastal forest systems to climate change has been the subject of ongoing scientific study, given the importance of such systems to tidal and near-shore ecosystem health. Mangrove ecologists therefore have developed rod surface elevation tables (RSETs) to quantify coastal wetland response to rising sea levels through periodic measurement of surface elevation change (SEC). The conventional method uses 36 individual pin measurements, relative to a levelled SET arm, to gauge the ground surface at precise locations surrounding the permanent RSET installation (Lynch et al. 2015). Recently, a novel method was developed to collect elevation change measurements around SETs using a terrestrial laser scanner (Karger et al. 2021). The new method can produce a centimeter-scale digital elevation model (DEM) in a two-meter radius circle surrounding an RSET. A superior SEC measurement to the traditional pin method is achieved by subtracting a previous time-stamped DEM. The recent advent of cellular device light detection and ranging (LiDAR) sensors, combined with a wide-angle camera, is an attractive alternative to both previous measurement procedures.

Methods: We measured a newly installed RSET network on Babeldaob, the largest island of the Republic of Palau, in the spring of 2024. Measurements were conducted using the traditional pin method, a terrestrial laser scanner, and an iPhone for comparison.

Results: The iPhone-LiDAR approach proved superior in instrument weight, measurement duration, and root occlusion avoidance, while requiring reduced user expertise on a familiar platform. A site can be rapidly scanned to produced high-fidelity RGB-colored point-clouds with ground measurements rivalling the terrestrial laser scanning approach (~100,000 1-cm square pixels vs. 36 points for the pin method) while maintaining sub-cm scale error for relative plot elevation surrounding an RSET. A careful scanning protocol is operationally feasible and requires forestry technicians to carry lighter and less awkward equipment through complex mangrove forests.

Conclusion: iPhone scans conducted by forestry technicians can subsequently be uploaded to the cloud for offsite-processing by point cloud data processing experts. This developing method has the potential to vastly reduce the time spent measuring ground elevation (minutes vs. hours) in mangrove forest plots, freeing up time for additional soil and forest inventory measurements at infrequently visited remote sites.

Monitoring forest attributes, C-fluxes, and C-stock in the Italian forests through a process-based model (3D-CMCC-FEM)

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Introduction/Aim: Process-based Forest models (PBFM) are relevant tools for investigating climate change effects and alternative management strategies. However, they can also be considered a valuable and complementary tool for monitoring forest conditions and their dynamics over short- to long-periods when ancillary data are poor and continuous measurements are costly and time-demanding over large areas. Thanks to the implementation of key ecophysiological processes, PBFMs account for the impact of climate and local competition for resources on tree growth. This study aims to evaluate the PBFM named '3D-CMCC-FEM' (Three-Dimensional - Coupled Model Carbon Cycle - Forest Ecosystem Module) on the capacity to simulate Italian forests' structural variables, C-fluxes and C-stocks and, thus, its monitoring capacity. The model simulations for the period 2005-2020 were tested for a subset of field plots as part of the third Italian National Forest Inventory (Inventario Nazionale delle Foreste e dei Serbatoi di Carbonio – INFC 2015) measured between 2017 and 2020 for a total of 1615 plots and nine different species along a wide environmental gradient.

Methods: The 3D-CMCC-FEM model was forced by daily climate data at 2.2 km spatial resolution and a national soil database at 250 m resolution and initialized with the plot-level structural information derived from the second Italian NFI for 2005. The model was used to predict the most common structural variables, such as diameter at breast height (DBH), tree height (H), basal area (BA), growing stock volume (GSV), carbon stocks (CS), tree density, and current annual volume increment (CAI), and validated against field observations from the third Italian NFI (2017-2020). In addition, we compared the gross primary productivity (GPP) against well-known RS datasets for the whole simulated period (2005-2020).

Results: Overall, the model was well-suited to reproducing the main stocks and structural variables with R^2 ranging between 0.71 (CS) and 0.46 (H) and RMSE% between 30% (DBH and H) and 40% (BA, GSV, and CS). The four most represented species (Q. cerris, F. sylvatica, C. sativa, and P. nigra), corresponding overall to 84% of the whole simulated plots, with the best results in terms both of RMSE% and R^2 for the DBH, CS and GSV. In contrast, the modeled GPP showed higher variability than the RS-based data, obtaining an overall RMSE% of 54% and 49% against the MODIS and GOSIF datasets, respectively. Overall, the best agreement was found against the GOSIF dataset, and the best-simulated species were C. sativa and F. sylvatica (33% and 34%, respectively).

Conclusion: The outputs from the 3D-CMCC-FEM model have shown consistent reliability, establishing it as a valuable tool for monitoring forests across large spatial scales up to daily temporal resolution. This approach performs similarly to RS-based approaches while offering increasingly continuous temporal data. Furthermore, it can be used to track GSV and CS changes between NFI surveys at local and national scales. Thus, it establishes a forest monitoring system to meet governmental interests in updated GHG emissions inventories and private entities in carbon offset investments.

The European Forest Disturbance Atlas: Towards an Operational monitoring of Forest Dynamics using the Landsat archive

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Forests disturbances have increased sharply in response to climate and land use changes in recent decades. Changes in disturbances have strong impacts on forest dynamics, structure and demography, endangering essential ecosystem services to society. The risk of losing important ecosystem services is strongly related to interactions between individual disturbance events, such as between insect outbreaks and windthrows, between individual fires (i.e. recurring fires) or also between natural disturbances and harvests. To better understand how increasing disturbances and their interactions impact Europe's forests and their ecosystem services, consistent and spatially explicit information on forest disturbances is urgently needed. We aimed at filling this gap by creating an exhaustive forest disturbance atlas for Europe, striving towards an operational monitoring system of forest dynamics.

The disturbance atlas is based on the full Landsat archive at 30 m resolution and covers over four decades (1984-2023). As a data basis we built a consistent data cube of ready-to-use Landsat surface reflectance data (including atmospheric and topographic corrections, as well as cloud and shadow masking) using FORCE (Frantz, 2019) and totalling to 115,663 images. Annual seamless gap-free composites were derived from the image database using the Best Available Pixel (BAP) selection algorithm, which choses high quality pixels closest to a target date (1st August ± 60 days) to avoid phenological changes and ensure intra-annual consistency while simultaneously avoiding clouds and other contaminations.

Based on the BAP images from a target year and the previous year, a Random Forest classification model was trained on manually labelled reference pixels (Senf, 2019) for mapping forest disturbances annually at the pixel level. Independent validation using 2,500 manually interpreted reference pixels stratified per country and forest area revealed map accuracies (measured as F1-score) of 0.75 and 0.98 for disturbed and undisturbed pixels, respectively. The pixel-based disturbance information was aggregated at the patch level and together with contextual information on the surrounding landscape assigned to a specific disturbance agent (bark beetle, fire, windthrow or harvest). Summarising annual disturbance maps over time ultimately allowed to detect multiple disturbance events per pixel and thus for the characterization of disturbance interactions (e.g., multiple fires, thinnings before final harvest).

The layers included in the European Forest Disturbance Atlas (Viana-Soto & Senf., 2023) provide insights not only into the year of disturbance, but also on the actual frequency of disturbances and the underlying causal agent, paving the road for a consistent disturbance monitoring system of Europe's forests. Upcoming improvements will advance the quantification of disturbance severity by means of vegetation and ground cover fractions using regression-based unmixing, thereby yielding information on, e.g., the percentage of tree cover loss at both the pixel and patch level. A first version of the maps can be explored online: https://albaviana.users.earthengine.app/view/european-forest-disturbance-map

Frantz, D. (2019). FORCE—Landsat+ Sentinel-2 analysis ready data and beyond. *Remote Sensing*, 11(9), 1124.

Evaluation of Forest Structure products for Characterizing Post-disturbance Landscapes and Green Tree Refugia

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Forest structure products within post-disturbance landscapes are critical research and management resources for characterizing residual structures as well as monitoring recoveries. It is important to understand the strengths and limitations of structure products within post-disturbance landscapes and how performance may vary across change agents, forest systems, change severities, and residual structures. In particular, post-disturbance canopy cover and height products are important for post-fire management planning, habitat assessments, as well as informing biomass patterns following disturbance events. While many national or regional products have associated validation assessments, they are rarely focused on post-disturbance landscapes which may represent novel structures and spectral signatures that can impact map performances. Horizontal cover mosaic patterns may also be important for informing post-disturbance management, such as identifying patches of live trees within post-fire landscapes, referred to as refugia. Post-fire refugia patches are particularly important for their role in different recovery strategies (e.g., seed trees, protection of seedlings from elements) as well as for habitat for species of conservation interest.

The overarching goal of our study was to provide validation assessments for a suite of remote sensing derived forest structure products, namely canopy cover and height, across a variety of post-disturbance landscapes (e.g., harvest, fire, and insects) and forest types of the western U.S. Furthermore, we aimed to test the performance of structure product suites for identifying and characterizing post-fire live tree refugia patches. Leveraging a set of airborne lidar validation collections, we provide comparisons in map performances and critical biases for a focal set of 30 m resolution structure products that includes our previously released GEDI-fusion gridded products (cover and relative height 98) and the NLCD Tree Canopy Cover products. We generally found lower map performances within post-disturbance patches for all map products compared to undisturbed forest, although the magnitude of those differences and associated biases varied by map product, change agent, and post-disturbance structures. We will further present comparisons of the focal cover and height products, as well as exploration into the value of data combinations, for identifying and characterizing green tree refugia patches to inform post-fire monitoring and planning applications. The validation assessments and exploration into data combinations for characterizing green-tree refugia will inform model improvements for the development of a suite of post-fire specific GEDI-fusion structure products and their use within habitat modeling applications.

Improved Area Estimation Technique based on the Stratification of Forest and Forest change area using a Continuous Probability Layer.

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Introduction/Aim:
Precise estimates of forest area and change help nations meet their reporting obligations under various international agreements and are a requirement to receive payments for verified reductions in carbon emissions under carbon accounting standards. During the last decade many countries used sample-based methods to report unbiased area estimates of deforestation to the United Nations Framework Convention on Climate Change (UNFCCC). Change is rare relative to large, stable land cover classes and estimates are challenging to obtain with sufficient precision to judge progress towards the desired goal of reducing deforestation over time. Failure to produce precise estimates can prohibit countries from taking advantage of funding and impact efforts to mitigate or adapt to climate change.

The statistics for sample-based area estimation are well established. Large-scale, operational application of the statistics to meet rigorous climate finance criteria, however, is novel and challenging. Stratified area estimation, in which a categorical map of stable forest and non-forest, plus additional change classes, are used to design and distribute a sample for reference data collection is often employed to reduce uncertainties around area estimates as much as practicable. However, the stratification layer is prone to error, which in turn leads to omission of changes in the stable strata being included in the reference data. Under optimal sample allocation, those reference samples typically have a huge weight in the estimation process and inflate the uncertainty beyond acceptable levels. The introduction of a spatial buffer stratum that accompanies most of those omissions has been useful, but not always successful.

Method & Results:
To practically improve precision of area estimates, we propose a general framework based on a continuous layer of forest change probability, accommodating all possible change categories. The forest change probability proxy variable is calculated using well-known remote sensing techniques such as dense time-series analysis and other approaches of characterizing land cover change. Strata boundaries and subsequent sample unit allocation follows, specifically designed to address, and alleviate the issue of omission of change in the stratification. Essentially, the procedure establishes a statistical buffer stratum based on the change probability layer. Additional statistical estimators to improve precision are also introduced. The theoretical concept is accompanied by results from simulations and real-world examples in the context of international carbon finance.

A Comparison of Tree Species Diversity among Montane Forest Fragments in the Taita Hills of Kenya using Hyperspectral Remote Sensing

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The fragmentation of forests into disconnected fragments in human-modified landscapes causes changes in the arrangement of plant communities and is considered a significant global threat to biodiversity. The tropical montane forests of the Eastern Arc Mountains in East Africa are a global biodiversity hotspot, hosting an exceptionally diverse range of organisms. However, due to agricultural expansion, these rainforests have been fragmented into isolated forest fragments, and the remaining forests have suffered from selective logging and the planting of exotic tree species. The biodiversity of such forest fragments can be examined at two levels: the diversity within the forests (α-diversity) and the diversity among the forests (β-diversity). Hyperspectral remote sensing offers a way to study both α- and β-diversity by using spectral diversity as a proxy for species diversity, a concept known as spectral species. Yet, the biodiversity of the East African montane forest fragments remains understudied, with no prior studies of their β-diversity.

We mapped and compared the tree species richness in montane forests of the Taita Hills in Kenya using AisaKestrel10 airborne hyperspectral data in the spectral range of 400-1000nm and a spatial resolution of 70cm. First, we calculated a minimum noise fraction (MNF) transformation to reduce the noise and dimensionality of the data. Then, we segmented the transformed data based on pixel similarity and distance using an extended version of the Simple Linear Iterative Clustering (SLIC) algorithm. After this, we calculated average MNF values for the crowns and classified them into spectral species using unsupervised K-means clustering. To calibrate the parameters of the clustering and to validate the classification, we used a set of 0.1ha field plots, where the number of tree species had been identified. Finally, we used the resulting spectral species maps to explore the α- and β-diversity. The results reveal how tree species diversity varies within and among these montane forest fragments, providing valuable information to guide conservation and reforestation efforts.

Exploring the Effects and Resilience of Subtropical Montane Cloud Forests to Seasonal Droughts and Typhoon disturbances through Multiple-scale Analysis

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Introduction/Aim:
Montane cloud forests (MCFs) are unique ecosystems frequently immersed by fog and low-stratus clouds (FLS). Climate change and elevated temperatures may amplify seasonal drought and typhoon intensity in recent decades, but their long-term impacts on MCFs remain unclear.

Methods:
In this study, we conducted cross-scale assessment using 6-year (2016-2021) ground litterfall and 21 year (2001-2021) satellite greenness data (the Enhanced Vegetation Index [EVI] and the EVI anomaly change [ΔEVI%]), gross primary productivity anomaly change (ΔGPP%), and meteorological variables (the standardized precipitation index [SPI] and wind speed) to explore the impact of disturbance on vegetation and the overall resilience of MCFs.

Results:
Our findings revealed that positive correlations between vegetation damages (EVI and ΔEVI%), productivity losses (ΔGPP%), and drought/typhoon severities imply that amplification of these disturbances could pose a great risk to MCFs in the foreseeable future. We found that MCFs are more susceptible to chronic seasonal drought than to acute typhoons, indicating that high precipitation and frequent fog immersion may not effectively mitigate the effect of water deficit but instead make the ecosystem more susceptible to drought. Moreover, vegetation regrowth during the winter can be considered as a manifestation of ecological resilience in MCFs, enabling partially recovery from forest productivity losses caused by severe disturbance in the preceding summer. Conversely, the absence of severe disturbance during summer may trigger defoliation rather than regrowth in the subsequent winter. These phenomena highlight the capacity of MCFs for self-adjustment and resilience in response to summer perturbations. In the long-term, our results indicated an increase in vegetation resilience over two decades in MCFs, likely driven by rising temperatures and elevated carbon dioxide levels.

Conclusion:
The enhancement of resilience might be overshadowed by the potential intensified droughts and typhoons in the future, potentially causing severe damage and insufficient recovery times for MCFs, thus raising concerns about uncertainties regarding their sustained resilience.

Pre-visual and early detection of myrtle rust on rose apple using hyperspectral and thermal indices

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Introduction:
Myrtle rust, caused by the fungus *Austropuccinia psidii*, is a serious disease, that affects many Myrtaceae species. Commercial nurseries that propagate Myrtaceae spp. are prone to myrtle rust and require a reliable method that allows pre-visual and early detection of the disease.

Objectives:
This study uses time-series thermal imagery and visible-to-short-infrared spectroscopy measurements acquired over 10 days from 81 rose apple plants (*Syzygium jambos* (L.) Alston) that were either inoculated with myrtle rust or maintained disease free. Using these data the objectives were to (i) quantify the accuracy of models using thermal indices and narrowband hyperspectral indices (NBHI) for pre-visual and early detection of myrtle rust using data from older resistant green leaves and young susceptible red leaves and (ii) identify the most important NBHI and thermal indices for disease detection.

Results:
Using predictions made on a validation dataset, models using indices derived from thermal imagery were able to perfectly (F1 score = 1.0; accuracy = 100%) pre-visually distinguish control from infected plants one day before symptoms appeared (1 DBS) and for all stages after early symptoms appeared. Compared with control plants, plants with myrtle rust had lower and more variable normalised canopy temperature, which was associated with higher stomatal conductance and transpiration. Using NBHI derived from older resistant green leaves, excellent pre-visual classification was achieved 3 DBS, 2 DBS and 1 DBS (F1 score range = 0.89 to 0.94).

Conclusion:
The accurate characterisation of MR during pre-visual and early stages of disease development suggests that a robust detection methodology could be developed within a nursery setting.

Development of a Sustainable Framework for Monitoring Guyana's Forests

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Introduction
The impact of global warming due to the continued rise of atmospheric CO_2 is well documented, with climate change a real threat to the Earth's ability to sustain life. Tropical forest conversion is estimated to contribute 12 to 30% of global carbon emissions. The Amazon is one of the tipping points of the Earth system-climate interaction. Feedback models of forest loss predict direct consequences for global climate that impact a far wider series of consequences, including rainfall shifts, forest dieback, and water availability[2]. Tropical forests are Guyana's most valuable land resource; they cover 87.5% of the landmass and are home to Amerindian peoples, representing 15% of Guyana's population.

Aim
Guyana, a high-forest, low-deforestation country, was a REDD+ early mover, signing a bilateral agreement with Norway in 2009.

Under the agreement, Guyana agreed to monitor its forest area and carbon loss using a series of interim indicators or measures. In return, Norway agreed to provide performance-based payments on an annual basis.

Methods
The approach developed is run by the Guyana Forestry Commission and uses satellite imagery to monitor and report forest loss at a 1 ha scale. Over time the system has evolved to leverage new satellites and improvements in cloud-based processing.

Conclusion
After thirteen years of continuous monitoring, the framework developed provides invaluable insight into national forest loss trends while also allowing Guyana to transition to a position where, in exchange for protecting forests, the country is financially rewarded for the carbon credits generated.

Satellite and Airborne remote Sensing Technologies in the process of Long-term Monitoring of Urban Biologically Active Areas (UBAA) as a Tools for Mitigating Climate Changes – A case study of city of Krakow (Poland)

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Actions to mitigate the negative effects of climate change should be based on continuous monitoring, management and support of activities in urban green spaces (UGS) in all forms of ownership. The definition of urban forestry (UF), apart from tree stands, includes groups of trees and shrubs in parks, squares, recreational areas, cemeteries, roof gardens, individual street trees and shrubs, herbaceous vegetation, lawns, flower beds, greenery in allotment gardens and private gardens, monastery gardens and other locations. For the purposes of the presented project, the definition of UF has been extended to Urban Biologically Active Areas (UBAA), which additionally included agricultural crops (orchards, fruit plantations, vineyards), cereal crops, vegetables and permanent grasslands - capable of sequestering CO_2 and producing oxygen, absorbing pollutants and limiting rain runoff. These key ecosystem services (ES) are provided by UBAA to the city's residents
Advanced methods for monitoring the condition of urban greenery are satellite and airborne remote sensing technologies such as VHRS optical imaging or ALS LiDAR point clouds. In the process of UBAA satellite monitoring (period 2006-2021) of the entire city of Krakow (326 km^2), the GEOBIA approach was used, which in addition to the MS and PAN satellite imaging bands, analyzed the vegetation index (NDVI), normalized surface models (nDSM/CHM), ALS LiDAR point clouds and vector GIS (buildings footprints, roads and railways, waters, etc.). The spatial resolution of the images ranged from 0.31 m GSD (WorldView-3), through 0.5 m GSD (SkySat), 0.64 m GSD (QucikBird-2), 0.7 m GSD (KOMPSAT-3), 1.0 m (IKONOS-2), 3.0 m GSD PlanetScope Dove, 5.0 m (RapidEye) to 10 m GSD (Sentinel-2, ESA). The density of the ALS LiDAR point cloud ranged from 18 to 30 points/m^2 (2006, 2012, 2017, 2021).
The results clearly show that UBAA decreased in the area from 76.1% (2006) to 71.29% (2021) during the monitoring period, which shows a clear trend (-4.81%). Over 15 years, as much as 1,626 ha (4.99%) of UBAA disappeared in Krakow, representing 104 ha of UBAA transformed annually into infrastructure (buildings, roads and areas without vegetation cover). This corresponds to an area of approximately 150 soccer stadiums per year.
Analyses based only on ALS LiDAR point clouds showed an increase in the area (2-D) of high vegetation (H>2 m AGL) from 5,569.69 ha (17.04%) in 2006 to 9,206.27 ha (28.17%) in 2021. The tree crown area (CHM) increased (approx. 47%) from 10,131.85 m^2 (2006) to 14,983.86 m^2 (2021). The average annual increase of CHM was 323.47 ha. Detailed voxel analyzes in the period 2006-2021 for the 'Planty Krakowskie' Park (44 ha) showed a change in the volume of canopies (3-D) by approximately +21%, i.e. from 149,627 m^3 (2006) to 181,399 m^3 (2021), with an increase of 2-D area by approximately 14.6% (from 18.45 to 21.15 ha).
GEOBIA satellite image classification and GIS analyzes have shown that 71.5% of Krakow's UBAA is not in public ownership. Therefore, it is so important to continue satellite monitoring and work with owners to support them to preserve as much green infrastructure as possible.

Crowdsourced Forest Information for Improving Forest aboveground Biomass estimates

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Increasing availability of open-access satellite data and computational technologies have opened up new possibilities in monitoring forests at large-scales. Nowadays, the earth surface can be observed from space in great geometric and radiometric detail at short time intervals. This offers immense potential for gaining novel insights into the condition and dynamics of global forests. However, realising the power of this big data paradigm requires access to high-quality and large-volume in-situ data which are laborious to obtain and, if present at all, are often not publicly available.

The Austrian research project “Citizens for Copernicus” (C4C), aims at bridging this data-gap by involving the public in the process of forest inventorying, thereby creating a citizen science (CS) based in-situ forest database for Austria. Combining the gathered CS data with imagery obtained from Copernicus’ Sentinel-1 and Sentinel-2 satellites to create a machine-learning ready database has the potential to substantially improve estimates of aboveground biomass and tree species maps. At the same time, through actively involving citizens in the building of scientific knowledge, the aim is to boost interest levels and foster trust in scientific methodologies and processes. The backbone of this initiative is a user-friendly smartphone application, which integrates various smartphone sensors, such as the camera, accelerometer and gyroscope, with state-of-the art computer vision and augmented reality functionality to collect accurate in-situ data on stem diameter, tree height and tree species. The application is based on standard smartphone hardware, thus ensuring widespread accessibility and availability for Android and iOS.

This presentation will introduce the C4C project, provide an overview of state-of-the art smartphone-based forest inventorying methods and present challenges associated with the large-scale application of citizen-science based forest inventorying. Furthermore, we will present first results from the CS campaign and compare estimates generated with the citizen-science app with traditionally (i.e. calliper, TLS) acquired reference data.

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A Spatiotemporal Data Fusion Strategy for Forest Mapping and Monitoring in Semi-Arid Environments

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Given their integral part in ecosystem function through the preservation of biodiversity and wildlife habitat, climate regulation, and carbon sequestration as well as their importance to local communities and the economy, robust and efficient methods for monitoring forests are of critical importance. In semi-arid regions such as sub-Saharan West Africa, this is especially true considering forests' role in conserving water resources, maintaining healthy and productive soils, and preventing desertification. In Senegal, where a majority of its inhabitants live in rural areas and earn their living from smallholder farming or pastoralism, trees are used for much more than their timber. They are heavily relied upon for shade during cultivation and for grazing animals, as well as for medicinal purposes and charcoal, an important source of fuel. In addition to deforestation, excessive use of these activities such as charcoal harvesting and overgrazing threaten the health of forests by contributing to degradation, making the monitoring of such changes important for enabling sustainable resource management.

However, forests in these dryland agriculture regions are often sparse and fragmented, characterized by a mix of dry deciduous forest patches and savannah woodland tree stands, as well as individual trees within agricultural fields. These distinct landscapes can make it difficult to adequately map and monitor forests with standard remote sensing methods and moderate to coarse resolution satellite data. Conversely, Very High Resolution (VHR) data such as Maxar’s WorldView (WV) presents its own challenges in the context of land cover/land use change analyses due to their sporadic coverage throughout space and time, and lack of radiometric consistency between observations.

To address these challenges, we developed an object-based deep learning approach for mapping and monitoring changes in land use. We identify the conversion of forestry to agroforestry, agriculture, urban area, and degraded forests using a data-driven 1D Convolutional Neural Network (CNN) model, fuelled by a combination of VHR Multi-spectral data from WV and SAR time-series from Sentinel-1. A domain-agnostic data fusion strategy is used to combine these datasets at a variety of spatial and temporal scales for time series monitoring. Additional data-driven and morphological methods are used to individually characterize agroforestry objects. Independent validation on the initial model results, substantiated by in-situ observations collected on a recent field campaign to Senegal, reveals an overall classification accuracy greater than 75%. The science output from this model includes a georeferenced temporal land use database that can be used for change detection in forests and subsequent resource management and conservation efforts.

Tree Canopy Cover Recovery of Southern Yellow Pines after stand-replacing disturbances

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Introduction/Aim:

The United States Forest Service 2021.4 tree canopy cover product suite contains an annual science product derived from both Landsat and Sentinel-2 data spanning 2008-2021, but has not yet been evaluated for its potential utility in monitoring forest ecosystem recovery after stand-replacing disturbances in southern yellow pines.

Methods:

Southern yellow pines were identified by selecting areas classified as evergreen in at least six of eight United States National Land Cover Database epochs and no more than two shrub epochs. 651 independent locations of pine forests with stand-clearing disturbances between 1986 and 2011 were identified using a 70% confidence of fast loss in the Landscape Change Monitoring System. We calculated stand ages using the fast loss disturbance, resulting in values of tree canopy cover from age 0 to 35 years. We calculated mean tree canopy cover at each age to assess regional patterns of tree canopy recovery after disturbance.

Results:

Results show the mean annualized tree canopy cover data following a trajectory of sharp increase after disturbance. Tree canopy cover begins to level off at approximately 80-85% at approximately age ten and decreases after age 30. The pattern follows the expected trajectory of regrowth, as seen in our prior work with other indicators, such as the enhanced vegetation index. Our results suggest that annualized tree canopy cover opens new possibilities for assessing canopy recovery after disturbance, enabling biophysically meaningful and spatially specific assessments of climatic, edaphic, and anthropogenic drivers.

Incorporating Spatial Heterogeneity into Model-Assisted Estimator to Improve Small Area Estimation

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Precise small area estimation of forest characteristics, such as forest area, forest biomass, forest volume and carbon are often difficult because of limited sample sizes. To increase the precision of estimates, model-assisted regression estimators which take advantage from remote sensed auxiliary data are increasingly used for the USDA Forest Service Inventory and Analysis programs. Spatial heterogeneity, also known as spatial nonstationary, is a fundamental characteristic for geographically spatial populations, however, randomly selected field plots using quasi-systematic sampling from geographical forest population cannot guarantee a “spatially balanced” distribution across the study area, and spatial heterogeneity in model residuals would be a potential problem when building regression models using sample data in model-assisted estimator. There are numerous area-level approaches that account for spatial heterogeneity, for example, spatial Fay–Herriot models provide a smooth spatial adjustment by including both the mean-zero spatial random coefficient and spatial random error, and this area-level model has been applied to forest biomass and volume estimation. In contrast to the situation with area-level models, far fewer studies have evaluated or implemented unit-level models that account for spatial heterogeneity in model-assisted estimator in small area estimation of forest characteristics.

Geographically Weighted Regression (GWR) is an effective way to deal with the spatial heterogeneity of model residuals and model coefficients. GWR was first introduced in geography to model variations in relationships between variables over space and it has been widely used in the fields of geography and environment. GWR is an extension of ordinary least squares regression but allows the model relationships to vary across space based on detecting where locally weighted regression coefficients deviate from global coefficients. This study introduces and develops a unit level GWR model-assisted estimator to estimate forest characteristics in small area estimation. The estimators were evaluated using Monte-Carlo simulation applied to both constructed populations and operational FIA sample data with full coverage of area remote sensing auxiliary data across the state of Virginia. Variances and standard errors of the estimates from GWR model-assisted estimator are compared with the variances and standard errors of the estimates estimated from Horvitz-Thompson estimator, poststratified estimator, and generalized regression estimator under the design-based inference. For the constructed populations, the GWR model-assisted estimator has smaller variances and standard errors than other estimators in populations with moderate or strong spatial variation. For operational FIA applications, GWR model-assisted estimator provided much smaller variances and standard errors than Horvitz-Thompson estimator, and the variances and standard errors are smaller than model-assisted estimator use generalized regression model. GWR model-assisted estimator provides an efficient way to improve the precision of the estimates through improving local predictions of target variable from the regression model. With the efficiency and simplicity of GWR model, the proposed GWR model-assisted estimator could be served as a practical method to estimate the forest characteristics in small area estimation. Further study is needed to evaluate the efficiency of other model-assisted estimators using spatial models.

Forest Age estimation in New Zealand's small-scale Plantation Forests: Integrating LiDAR-derived Height metrics, Site productivity with automated Harvest Detection

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The National Exotic Forest Description (NEFD) is a database that describes New Zealand's exotic planted production forests. Among the 1.76 million hectares of planted forests, approximately 30% are categorised as small-scale (<1000 hectares). However, NEFD has been noted to be inaccurate in the estimates of small-scale forests, particularly for those under 100 hectares. This has led to an insufficient understanding of the wood supply from these forests, posing challenges as the majority of them are approaching maturity and are anticipated to contribute more than 40% of the wood supply in the next decade. Accurate assessing forest age is crucial for understanding regional wood availability and facilitating effective planning in marketing, harvesting, logistics, and transport capacity. However, due to the impracticality of collecting information from individual forest owners, the age of small-scale forests remains unexplored.

The availability of remote sensing data, such as publicly accessible LiDAR and Sentinel imagery, presents an opportunity to estimate the age of these small and fragmented forests. This research aims to develop a method for estimating forest stand age in the East Coast wood supply region of New Zealand. Initially, annual forest harvesting was identified using a random forest classifier with annual Sentinel-2 mosaics collected from 2016 to 2022. For harvested forest stands, age was estimated as the year of harvesting plus one, assuming trees are planted one year after harvesting. For unharvested stands, as forest age and height are closely related, age was calculated inversely from a national height-age model, incorporating LiDAR-derived H99 as a proxy for Mean Top Height (MTH), site index, latitude, and elevation of each forest stand.

The harvest detection approach using random forest effectively identified harvested areas, achieving overall accuracies above 0.98. Forest age was estimated for all small-scale forests in the East Coast, ranging from 1 to 56 years. Preliminary assessment compared the estimated stand age with actual stand age information collected from forest growers, resulting in an R^2 of 0.93, with a Mean Absolute Error (MAE) of 1.86 years and a Root Mean Square Error (RMSE) of 3.26 years. The age-class distribution of small-scale forests in the region differed significantly from the NEFD. Our estimates showed considerably less area for older stands and more area for young stands, indicating that NEFD does not account for the harvesting and replanting of these resources. This study demonstrates that using remote sensing data can accurately estimate age for small and fragmented small-scale plantation forests, which is crucial for regional planning and management of these resources.

Mapping Functional Old Growth using Species distribution Modeling with Earth Observations

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Old-growth forests play a critical role in mitigating climate change and fighting against biodiversity loss. Information about where old growth is and how it changes over time will provide foundational management insight. Earth observations have often been used to map forest attributes, including canopy cover, forest height, and forest biomass, that are then used to identify old-growth forest on a structural basis.

In this study, we present a framework of monitoring old-growth forest through the lens of biodiversity using species distribution models. We analyzed 450 species from eBird data in California, Oregon, Washington, Idaho, and Montana. Only species with at least 30 observations from 2010 to 2023 were included in the analysis. Landsat surface reflectance from 1984 to 2023 was processed using continuous change detection algorithms to characterize spectral trajectories for the study area. For each species, a species distribution model was built using Maxent. All the SDM models for old-growth indicator species were integrated to calculate a relative old-growth forest score. The resulting SDM-based old maps can be evaluated together with land surface disturbance to understand old-growth dynamics.

Assessing the Impact of Forest Fires on Ecosystem Services: A Scoping Literature Review and Proposing a New Framework

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This study explores the extensive impacts of wildfires on global forest ecosystems, highlighting their significant effects across economic, environmental, and social dimensions. Through a comprehensive scoping literature review, various economic valuation methodologies are evaluated, encompassing both market and non-market assessment techniques. Notable methods include the Faustmann and Reed model for assessing market impacts, alongside stated and revealed preference approaches for evaluating non-market environmental values. Additionally, insights from ecological models provide further understanding of the indicative environmental impacts of wildfires.

A significant finding from our review, based on the work of Wang and Lewis (2024), quantifies the economic impacts of wildfires on timberland value in the Pacific states of the USA. Their analysis documents a substantial 10% decrease in timberland economic value attributed to extensive wildfires and prolonged drought stress over the past two decades. Furthermore, comparative financial analysis by Blick and Woon (2021) indicates greater economic losses in forested areas compared to scrub and pasture lands in New Zealand.

In the context of non-market economic valuation literature, which remains very limited in the fire impact assessment space, the study by Farreras and Mavsar (2012) underscores a pronounced public preference for proactive wildfire prevention strategies over dead tree management. Furthermore, research by Loomis et al. (2001) illustrates the diverse impact of wildfires on recreational activities, with crown fires significantly altering the perceived value of hiking and mountain biking experiences.

From an ecological perspective, the global review by Roces-Diaz et al. (2022) indicates the complex effects of wildfires on ecosystem services, affecting water provision, quality, climate regulation, and erosion control in various ways.

Building upon these insights, we propose a novel conceptual framework that leverages remote sensing data for a nuanced evaluation of the multifaceted values of Forest Ecosystem Services (FES). This approach aims to refine the assessment of the costs and benefits associated with wildfire management programmes, considering both market and non-market values of FES, alongside distance and neighbourhood effects. By enhancing our understanding of the financial, environmental, and social repercussions of wildfires on FES, this research advocates for more effective forest management and a more targeted fire prevention approaches and outcomes. Our findings and proposed framework aim to inform future research, thereby contributing to the mitigation of wildfire-induced damages on local, national, and global scales.

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189

Implementation of Near-Real-Time monitoring tools in Sepal - methods and examples

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Implementation of Near-Real-Time monitoring tools_foressat2024.docx (could not be inserted)

Introduction/Aim:
Near real-time monitoring (NRTM) of forest resources is crucial for protecting existing resources and improving law enforcement efforts. However, easily accessible global NRTM systems often suffer from overestimation of alerts due to a lack of customization for geographic and local conditions. To address this limitation, the FAO forestry department developed easy-to-use, open-source functionalities as part of the SEPAL cloud computing platform.

Methods:
Two main methods are available through the platform. The first one is based on a tailored version of the Continuous Change Detection and Classification (CCDC) approach, as proposed by Zhu and Woodcock (2014), for rapid forest disturbance detection. As CCDC is data agnostic, the algorithm can either utilize a combination of Landsat and Sentinel-2, Sentinel-1 or Planet daily imagery.

The implementation of the BayTS algorithm allows users to access and customize the underlying method of the globally available RADD alerts, which is solely based on Sentinel-1 radar data to detect changes in forest.

Both methods can be fully customized by a set of parameters. In addition, the alerts can be easily masked by any kind of locally available forest mask. This allows users not only to optimize the algorithms for local conditions, but also to obtain ownership on the generated information, which might be critical for subsequent legal actions.

Results:
The tool has been tested in different countries and climatic zones and results were comparable or better with respect to other algorithms. Specifically alerts generated with the Planet daily imagery were generally both, timelier, as well as more spatially accurate due to the better temporal and spatial resolution.

Improving Neural Network Classification of Indigenous Forest in New Zealand with Phenological Features

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Accurate and up-to-date vegetation cover maps are essential for effective forest management and policy decisions. Phenological changes in spectral response captured by time-series data can potentially improve vegetation classification by distinguishing vegetation types more effectively. However, the specific phenological features that contribute most to classification of New Zealand's native forests remain unknown. Feature selection has been proven as an effective solution to this problem. This study aimed to evaluate phenological feature importance and selection for classifying a 50 km^2 native podocarp forest in New Zealand using two-year Sentinel-2 (S-2) time-series data and single-date PlanetScope (PS) imagery.

The study area was classified into nine classes. Single-date PS and S-2 data were fused to create a base image with the same spatial resolution as PS and eight spectral bands from S-2. This fused image was used to derive 30 Vegetation Indices (VIs). Phenological features, including amplitude (AMP) and phase (PH), were extracted from the VIs using harmonic analysis in Google Earth Engine based on the S-2 time-series data. Three classification scenarios (fused bands & VIs, fused bands & phenological features, fused bands & VIs & phenological features) were developed using a Neural Network to accurately classify forests and identify the most important features. Variable Selection Using Random Forest (VSURF) was applied to these scenarios to evaluate the impact of feature selection on classification accuracy and efficiency.

Results indicate that VSURF reduced the time needed for classification while maintaining comparable accuracy. The incorporation of phenological features improved accuracy from 90% to 94%, primarily driven by Red-Edge Triangulated Vegetation Index-AMP&PH, Normalised Near-Infrared-PH, Greenness Index-PH. These features reflect changes in the canopy's structure, biochemical, and physiological characteristics.

In conclusion, this study demonstrates that specific phenological features can improve the classification of New Zealand's indigenous podocarp forests. The methodology presented in this study offers a potential approach to refine the classification of forests in New Zealand, which could lead to better-informed decision-making and more effective management of the country's indigenous forest resources in the future.

Individual Tree Biomass Estimation of Durable Eucalyptus using UAV LiDAR

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Introduction/Aim:
Fast-growing and naturally durable eucalyptus species, including *Eucalyptus globoidea* (*E. globoidea*) and *Eucalyptus bosistoana* (*E. bosistoana*), growing in the Marlborough region of New Zealand, have the potential to enhance sustainability and reduce greenhouse gas emissions in the region's wine industry. There is a need for accurate estimation of total biomass production and total carbon sequestration. However, the extent of carbon sequestration by these eucalyptus species remains unexplored. This study aimed to efficiently and accurately estimate individual tree dimensions (diameter at breast height (DBH)) and above-ground biomass (AGB) for *E. globoidea* and *E. bosistoana* using light detection and ranging (LiDAR) data acquired by an unpiloted aerial vehicle (UAV) and destructive sampled ground truth data.

Methods:
LiDAR data were captured with a Zenmuse L1 LiDAR sensor mounted on a DJI Matrice 300 RTK drone over nine sites, followed by destructive sampling to quantify individual tree biomass. In total, 96 individual tree LiDAR metrics were extracted and were used as explanatory variables for training and predicting DBH and AGB models. Three machine learning (ML) models, including Partial Least Squares Regression (PLSR), Random Forest (RF), and Extreme Gradient Boosting (XGBoost), were trained using a grid-search strategy and repeated cross-validation. Model performance was evaluated using root mean square error (RMSE) and R^2, while SHapley Additive exPlanations (SHAP) analysis was employed to explain model predictions and evaluate input variables.

Results:
Preliminary results showed that among the ML models, XGBoost and PLSR demonstrated superior performance, with the former yielding the highest R^2 value of 0.861 and the lowest RMSE of 53.897 for AGB, and the latter achieving the highest R^2 value of 0.840 and the lowest RMSE of 3.657 for DBH. SHAP analysis highlighted that height and voxel metrics are the most important factors influencing AGB and DBH prediction.

Conclusion:
These findings prove that using UAV LiDAR could estimate carbon sequestration of eucalyptus plantations efficiently and accurately, and can support sustainable practices in the Marlborough region's wine industry.

Forest stand segmentation using Landsat and ALS-derived forest attributes

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Introduction/Aim:
Forest inventories are essential to support forest management and are typically developed using manual stand delineation from aerial imagery. Once stands are delineated, attributes are then estimated via visual interpretation and other established practices, including the use of field plots are used to calibrate and adjust the attributes. Both stand delineation and attribution processes associated with photointerpretation can be costly, time consuming, and subjective.

Methods:
We developed an open-source segmentation algorithm designed to automatically delineate forest stands from Landsat spectral reflectance data and a suite of Airborne Laser Scanning (ALS)-derived forest attributes, including height and height variation, gross stem volume, age, and species. To demonstrate the approach, we applied it over five focus sites totalling 45 Mha, representing the diversity of forest landscapes across Canada. In Phase 1, small groups of pixels from the Landsat imagery are grouped based on spectral similarity; in Phase 2, these pixel groups are further merged into forest segments based on the ALS-derived forest attributes. We used two spatial assessment metrics, area-weighted variance (wVar) and Moran’s I (MI), to characterize within-segment variance and between-segment spatial autocorrelation. Agreement between the Phase 2 segments and reference Provincial polygon inventories was assessed using the Adjusted Rand Index (ARI).

Results:
Our results showed that height variation minimized wVar in western Canada, while gross stem volume minimized wVar in boreal forests, indicating that stands are generally more homogeneous with respect to these attributes in these regions. Height variation consistently showed the lowest MI across Canada, resulting in stands that are heterogeneous from their neighboring stands. Segments combined using species information produced simpler boundary linework, as reflected in the high ARI value and more closely resembled the reference Provincial polygon inventories.

Conclusion:
Forests are constantly changing due to successional and growth processes as well as human and natural disturbances; as such, accurate and up-to-date forest inventories are needed to reflect the present status of forest resources. Our segmentation algorithm uses openly available Landsat imagery, open data products, and ALS-derived forest structure attributes to automatically and consistently delineate stands of different forest types across large forested regions, reducing human intervention and the limitations associated with photointerpretation techniques.

Forest Habitat Mapping: Comparison between Single-date Hyperspectral PRISMA and Multi-date Multispectral Planet and Sentinel-2

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The increasing availability of spaceborne hyperspectral satellite imagery opens for new opportunities in forest habitat mapping and monitoring. In this study, we explored the ability of PRISMA (PRecursore IperSpettrale della Missione Applicativa), the new hyperspectral satellite from the Italian Space Agency, to detect and correctly classify various forest habitat types distributed over a relatively small spatial extent (6000 ha) in a natural reserve in Central Italy. The case study deals with various level of spectral similarity, as the canopy dominant species of the target forest habitat classes are species of the same genus (*Quercus*, deciduous and evergreen species) or of different taxa (Pinus, Fraxinus). We performed a pixel-based classification with the Random Forest algorithm using a set of 28 spectral indexes computed on PRISMA bands. As comparison, we performed the RF classification using both single-date and a time series of Planet ad Sentinel-2 imagery, collected over the growing season, using the reduced set of spectral indices that can be calculated with two broad-band multi-spectral sensors, but across different decades. A Canopy Height Model was also used as input variable for the classification with the three sensors.

Our results showed that PRISMA considerably outperforms the two multispectral satellites on single-date classifications, with an overall accuracy of 82% compared to Planet’s 64% and Sentinel-2’s 68%. As for comparison with multi-date multispectral and single-date hyperspectral, 10-fold cross-validation results revealed that PRISMA and Planet both reach around 21% of error rate, while Sentinel-2 is around 19%. This proves that a combination of spectral indices calculated during the growing season can capture phenological or physiological differences among the targeted species, which consequently resulted in a significant improvement in the classification accuracy of the multi-spectral sensors.

Ultimately, classification results from all three sensors were combined in the creation of probability maps for each forest class, thus identifying the areas which were classified with a higher degree of certainty by every satellite.

Nationwide airborne laser scanning based models for leaf area index mapping in Finland

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Introduction/Aim:
Leaf area index (LAI) is an important parameter that describes the characteristics of forest ecosystems. It measures the amount of leaf material present in the canopy and is often used as an input in various biosphere-atmosphere models that describe mass and energy exchange processes (Ryu et al., 2011). In many countries, airborne laser scanning is routinely used to estimate forest attributes on national scale following an area-based approach (Maltamo et al., 2021). This technology has been successfully applied for the estimation of LAI as well (Solberg et al., 2009). Nevertheless, nationwide LAI maps are still absent, although they could be constructed based on nationwide ALS data acquisitions. This study aimed to assess the comparability of national and regional LAI regression models using ALS data.

Methods:
We collected digital hemispherical photographs as field reference data from 178 plots across five regions in Finland. Effective LAI was estimated from the photographs based on the Beer-Lambert law. We fitted nationwide and regional models using Ordinary Least Squares regression with two ALS-based predictors. All possible predictor combinations were tested and the ones that yielded the smallest relative root mean square error (RMSE%) were selected. The nationwide model was validated using leave-one-region-out and the regional models using leave-one-plot-out cross-validation.

Results:
The results showed that the nationwide and regional models yielded comparable results, but overall, the regional models provided slightly higher accuracy. The nationwide model had a cross-validated RMSE% of 19.9% while the regional model RMSEs ranged from 9.5% to 20.9%. When the nationwide model results were analysed by region, the RMSE% were 0.9%–10.3% larger compared to regional models. The regional models had better accuracy especially for larger effective LAI values. The most selected ALS predictors included logarithmic transformations of canopy penetration indices derived from either first and single or all echoes.

Conclusion:
Although different ALS acquisition settings may have an influence on the results, it is still possible to obtain reasonably accurate predictions with nationwide LAI models trained without local calibration data. However, on average the local models 4.5% smaller RMSE% than the nationwide model in all regions, which is consistent with previous findings of nationwide forest volume and biomass models (Kotivuori et al., 2016).

Table 1. Nationwide and regional effective LAI model accuracy

	Nationwide model	Regional models	Nationwide model by region
Pello		10.5%	12.0%
Merikarvia		20.9%	21.8%
Outokumpu	19.5%	9.5%	19.8%
Heinola		19.3%	23.8%
Hyytiälä		13.3%	18.8%

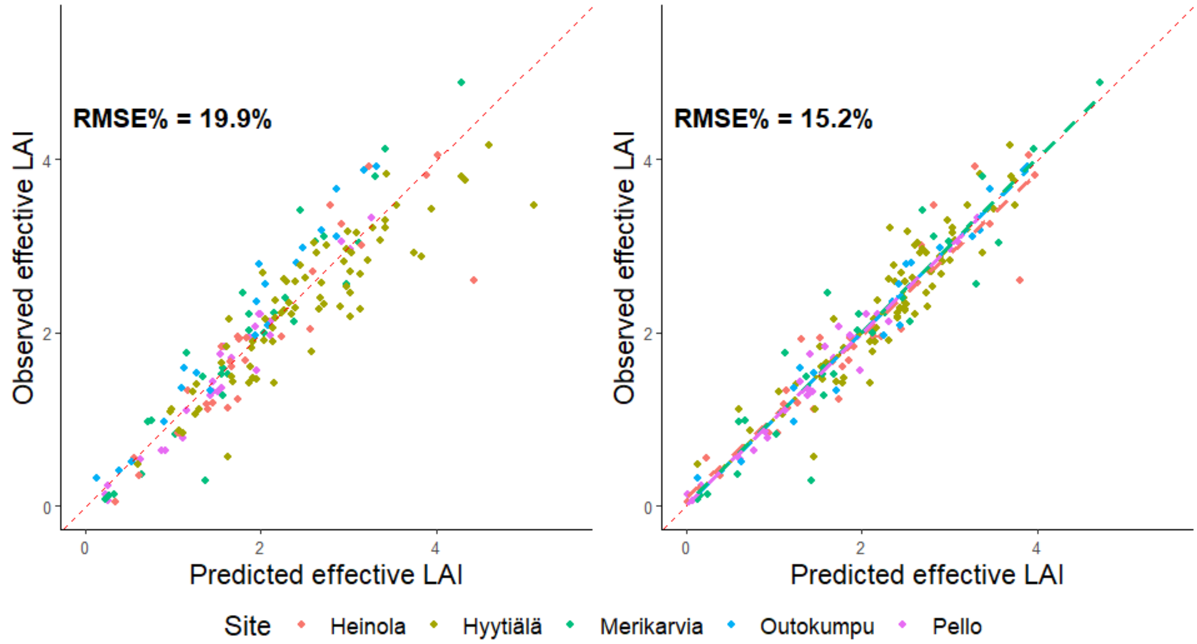

Figure 1. Effective LAI predicted by nationwide (left) and regional (right) models against observed counterparts.

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"Density × Volume": A non-Destructive Observation Technology of Tree aboveground Biomass

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As an indirect observation method, the tree anisotropic growth equation is prone to subjective errors, and the applicability of the equation varied in different environments, so this paper innovatively proposes a non-destructive observation technology of tree aboveground biomass of "density×volume". A multi-frequency microwave-based single-tree biomass density observation technology was proposed. Based on theoretical analysis and experimental measurement, microwave frequency applicable to different tree species and diameter level of woody plant density observation was explored. Then, by analyzing the changing laws of microwave characteristics, attenuation constants, aboveground biomass density, single-tree density observation model of different tree species was established, with an average error of 6%, accuracy of 94%, measurable diameter range of more than 60cm. By using height standardization of terrestrial and UAV LiDAR point cloud data, tree trunks were quickly detected by hierarchical clustering, and then multi-level distribution of individual trees was generated. For the clustered points of each level, the fast point feature histogram features were calculated, and then they were used to match the points of the distribution of the same level to obtain their transformation matrix, and finally through the iterative nearest point method, the further fine alignment was performed. The average goodness of fit obtained was 0.945, with an RMSE of 0.144. Using the single tree modelling approach, the branching patterns, geometric and volumetric characteristics of the trees were quantified, and the aboveground volumetric monitoring accuracy of the single trees reached 85%, with some species reaching more than 90%. Finally, the aboveground biomass of individual trees was calculated by multiplying the aboveground biomass density by the aboveground volume.

Monthly mapping of forest disturbances using dense time series Sentinel-1 SAR imagery and deep learning

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Introduction/Aim:
Compared with disturbance maps produced at annual time steps, high-resolution monthly mapping of forest disturbance can provide more spatio-temporal details needed for studying the socio-economic drivers (e.g., differentiating salvage logging and slash-and-burn from other timber harvesting) of disturbance and characterizing the associated intra-annual carbon and hydrological dynamics. Frequent cloud cover limits the application of optical remote sensing in timely mapping of forest changes. The freely available Sentinel-1 synthetic aperture radar (SAR) sensor provides an unprecedented opportunity to achieve more frequent mapping of forest disturbance than ever before (i.e., at monthly interval). The unique landscape pattern of forest disturbance from Sentienl-1 data holds critical information for disturbance mapping but have not been fully explored.

Methods:
In this study, we propose a deep learning-based approach ultilizing the landscape pattern from Sentinel-1 data to produce 10m monthly maps of forest disturbance for the whole Brazil for five years.

Results:
The proposed approach is reliable for monthly forest disturbance mapping with Sentinel-1 data, and can be trained using samples collected during a particular time period over one location and be fine-tuned using sparse local samples from a new area to achieve optimal performance, and hence can greatly reduce training data collection effort when applied to new study sites.

Conclusion:
Our novel approach for mapping forest disturbances at monthly interval represents an important step towards precise monitoring of forest dynamics and assisting stakeholders in developing sustainable strategy of forest management, especially for regions with frequent cloud cover.

Enhancing Individual Tree Detection and Species classification in an Urban Forest with Semi-Supervised Deep learning models

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Background:
Individual tree characteristics including crown locations, extents, and species are important inputs for effective urban forest management. In recent years, deep learning models have emerged as a popular tool for deriving these characteristics from remotely sensed imagery. Compared with traditional methods, deep learning shows advantages in learning complex visual features, which benefits tree recognition across urban scenes. However, training deep learning models usually requires a large number of samples covering varied urban scenes and crown types. Manually labelling these samples from remote sensing imagery demands significant time and effort. As a result, data scarcity becomes a major issue impeding the wider application of deep learning models in the urban forest domain.

Method/Result:
This study addressed the data scarcity issue by applying several semi-supervised learning (SSL) algorithms to high-resolution aerial imagery for two tasks: individual tree detection and individual crown species classification. The SSL algorithms enable the deep learning model to train on a large number of unlabelled remote sensing images to supplement scarcer-labelled training samples.

The approaches were tested on summer aerial imagery from Auckland city, New Zealand, with a resolution of 7.5 cm/pixel. The results showed that SSL effectively improved accuracies for both tasks compared with supervised approaches that used the same labelled data. In individual tree detection, the SSL model improved the mean average precision (mAP) by 0.5% to 1.9% on comparisons made on different sizes of training datasets. For individual crown species classification, our SSL approach achieved an F1 score of 87.09%, showing a 7% improvement compared to the supervised model, in the classification of five species, using only 50 training images per class.

Conclusion:
Our research highlights the potential of SSL as an effective strategy for reducing reliance on manually labelled samples in individual tree analysis. This is particularly important in the context of the urban forest domain, where training samples are often limited. The findings presented here contribute to the ongoing efforts aimed at improving data efficiency and generalisability when applying deep learning models across urban forest environments.

Mapping canopy heights by fusing optical, radar, and GEDI data in the Kruger National Park, South Africa

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Accurately mapping the canopy heights of savanna ecosystems is crucial for global biomass estimation, carbon cycling, and biodiversity. The emergence of spaceborne light detection and ranging (lidar) has shown great potential in wall-to-wall mapping the canopy height for sparse savanna ecosystems with its implicitly contained 3-D structural information. This research presents a successful development of a random-forest-based mapping method for savanna canopy heights. The method is based on various features, such as vegetation indices, texture information, and time-series features obtained from both passive (i.e., Sentinel-2 and Planet) and active (i.e., Sentinel-1, PALSAR, and GEDI) remotely sensed data in the Kruger National Park, South Africa. In addition, we distinguished between tree canopies and grass or shrubs using a tree-grass separation index. We also examined how topography, canopy cover, and land cover affect the predicted canopy heights in our study area. The study demonstrated that GEDI-based canopy heights can accurately capture the heterogeneous spatial distribution pattern in the horizontal dimension and effectively predict variations in canopy height model-based results in the vertical dimension (Pearson's r=0.682, RMSE=3.573m). The predicted canopy heights are significantly affected by topographic variations, while canopy cover variations have limited effects on the predictions. This work showcases the mapping of savanna canopy heights using GEDI and lays a foundation for future research on estimating aboveground biomass and characterizing biodiversity in regional or global scales.

Local Calibration of GEDI L4A Data with Lao National Forestry Inventory for Improved Above-Ground Biomass Estimation

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NASA's Global Ecosystem Dynamics Investigation (GEDI) presents an unprecedented opportunity for cost-effective estimations of Above-Ground Biomass Density (AGBD) using Light Detection and Ranging (LiDAR) technology from space. Yet the current performance of the GEDI Level 4A (L4A) AGBD product can significantly vary across different regions, subject to model choice and availability of calibration data. Here, we identified systematic biases in the current GEDI L4A AGBD product compared to National Forest Inventory (NFI) data for the Southeast Asian country of Laos, with absolute bias values ranging from -54.24 Mg/Ha to 106.23 Mg/Ha across different forest types, underscoring the limitation of using global models in specific local and regional contexts. Since the use of alternative L4A AGBD models was still not able to fully remove these biases, we optimised the GEDI L4A AGBD model configurations for natural forests in Laos and calibrated them with ancillary variables. Our approach significantly mitigated biases across various forest classes, with an average bias reduction of 42.2 Mg/Ha in absolute terms after calibration and the greatest reduction from an initial bias of 129.05 Mg/Ha to -13.33 Mg/Ha in the evergreen forests. The calibrated GEDI footprints were aggregated into a hexagonal grid overlain over Laos to create an AGBD map, with each cell of the grid having a diameter of 600m and aligning with the spatial scale of NFI survey plots to facilitate analysis. The approach also enabled the updating of national-level estimates of average AGBD stock for each forest class in Laos using a model-assisted estimator complementary to the existing NFI design-based estimator. Results highlight the importance of localised calibration in remote sensing applications used in estimating forest biomass, and not only enhance understanding of variations in biomass of different natural forest types in Laos but also offer a replicable framework for more accurate and efficient forest biomass estimation in other regions with limited availability of ground data and/or extensive, remote areas of forest.