

FORMEC 2026

BOOK OF ABSTRACTS



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**Enabling resilient forest value chains
through innovation**



Faculty of Forestry
and Wood Sciences

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Oral Presentations

Session 1

Seasonal Performance of Stand-Level Basal Area Estimation: A Comparative Study of a Smartphone LiDAR Application and Professional Personal Laser Scanning

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The digital transformation of forest inventories needs the validation of consumer-grade sensors over different phenological stages. This study evaluates the seasonal measurement agreement of stand-level basal area (BA) estimates and operational efficiency between the TreeScanner smartphone application and the FJD Trion P1 professional personal laser scanner (PLS). Research was conducted in fifty circular plots (300 m²) in heterogeneous forests (45–170 years) with rugged topography (slopes 8°–42°) in Braşov, Romania. The experimental design followed a five-dimensional logical order: inter-platform BA agreement within seasons, intra-platform BA variability across seasons for both devices, and seasonal stability of acquisition times for each platform independently. Results regarding inter-platform agreement for BA showed that winter (WI) achieved the highest precision (RMSE: 0.092 m²; Bias: -0.058 m²), while in autumn (AU) it reached statistical parity (paired t-test, $p=0.0926$). Conversely, spring (SP) exhibited the lowest agreement (RMSE: 0.391 m²; Bias: -0.184 m²) due to vegetative noise. Intra-platform analysis revealed that BA estimates derived from TreeScanner varied significantly between seasons ($p < 0.05$), primarily influenced by the leaf emergence cycle and annual diameter increments. In contrast, the FJD Trion P1 data ($p < 0.05$), was significantly impacted by seasonal environmental constraints, such as understory regrowth and climatic variables including snow, mud, or rain. In terms of efficiency of operation, the TreeScanner application, which records the time to scan each tree individually, maintained an inter-season stable non-different ($p > 0.05$) rate of acquisition (16s/tree approx.). Conversely, the FJD Trion P1, which records the total time to scan the plot, was found to vary significantly ($p < 0.05$), as its performance proved more sensitive to structural obstructions like growing shrubs and seasonal factors such as snow and rain-induced terrain difficult. It is concluded that Smartphone LiDAR technology is a mature technology for rapid forest inventories with professional-grade agreement during the leaf-off period and better temporal stability than the professional standard.

Keywords: Mobile LiDAR, forest inventory, measurement agreement, phenological cycle, operational efficiency, basal area, personal laser scanning.

Keywords: Mobile-LiDAR1; personal-laser-scanning2; measurement-agreement3; operational-efficiency4

Intelligent Image-Based Detection of Wood Features for Improved Material Sorting in Forest-Based Value Chains

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Reliable, high-throughput evaluation of internal wood quality is a critical enabler for modern mechanized forestry and downstream processing. We report a compact set of results from an imaging-based workflow for automated analysis of roundwood, focusing on (i) robust separation of bark from solid wood and (ii) consistent detection of slices containing internal defects such as knots, cracks, or degraded tissue.

Data and approach: We trained a three-class semantic segmentation model on annotated log images with voxel dimensions of $1 \times 1 \times 10$ mm. The training set was deliberately enriched with difficult cases, especially slices with discontinuous or partially peeled bark. To stabilize edge decisions with minimal computational overhead, we added a one-step adaptive relabeling rule that converts specific high-intensity peripheral pixels—frequently misinterpreted as background—into the bark class. For defect presence/absence, we introduced a composite multi-layer representation by merging three consecutive slices into a single input image, thus injecting short-range spatial context without resorting to full volumetric modeling.

Results — bark segmentation: On a 50-image validation subset, the Sørensen–Dice score for bark reached 0.704 (wood 0.981, periphery 0.996). Applying the single adaptive relabeling step increased bark Dice to 0.750, while maintaining wood at 0.981 and periphery at 0.999. The improvement held for both slices with defects and defect-free slices, indicating that the rule targets a systematic boundary issue rather than overfitting to specific textures.

Results — defect detection: Single-slice classification achieved 93.94% overall accuracy across logs. Introducing the three-slice composite raised accuracy to 95.39% and increased the worst-case per-log performance above 92%, evidencing greater robustness to inter-log variability. When the inter-slice distance in the composite was increased to 2 cm, the accuracy reached 94.72%, suggesting diminishing returns once the composite exceeds the typical continuity scale of internal features. Class-wise diagnostics further showed that pronounced dark regions associated with unhealthy knots, decay, and major cracks were detected with near-certain confidence, whereas subtle, healthy-knot transitions remained the primary challenge.

Implications for technology and operations: Three pragmatic interventions—targeted inclusion of difficult bark cases, a single adaptive post-processing rule, and composite multi-slice inputs—deliver measurable gains in segmentation reliability and defect detection while keeping the computational and operational footprint low. Such lightweight improvements can be integrated into mechanized inspection chains to support more dependable sorting, planning, and value recovery decisions in forest-based value chains.

Keywords: CT-imaging; deep-learning; bark-segmentation; defect-detection

Thinning Mediterranean pine forests with innovative and traditional light equipment: comparison of work productivity and damages to the remaining trees

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In Mediterranean forestry, thinning of pine forests is mainly done with traditional harvesting system (THS) due to its versatility and low investment and relocation costs compared to specialized machinery. However, THS is based on winch coupled to farm tractor with a large share of manual work for felling and processing tasks. The increasing lack of workforce for these activities may be solved with the introduction of highly mechanized systems. In this context, light multipurpose machinery harvesting system (LMM) may be a valuable alternative, providing a fully mechanized solution with an affordable initial investment and limited relocation costs. To assess its feasibility the performance of a LMM constituted by a unique harvester-forwarder combi machine, has been compared to the THS. The results show highest overall productivities of THS (2.87 m³/PMH15) compared to LMM (2.3 m³/PMH15). Yet, due to the higher hourly cost of the traditional system overall harvesting costs are lower in the LMM (38.8 €/m³) than in THS (39.7 €/m³). Additionally, LMM provides a larger number of timber assortments, leading to a higher value recovery with a difference of 4.5 €/m³ compared to THS. This provides an economic balance per m³ over threefold higher in LMM. Concerning damage assessment, the THS caused higher number of injured trees (8.5%) compared to LMM (2.8%), yet in both cases overall damages to the remaining stand are limited.

Keywords: Light-machinery; Productivity; Thinning; Damage

Assessing Soil Trafficability Mapping as a Decision-Support Tool for Minimising Harvesting Impacts in New Zealand Forests

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Ground-based forest harvesting operations can substantially disturb soil through mechanisms such as compaction and rutting, posing long-term risks to forest productivity and sustainability. In boreal forest systems, soil trafficability maps derived from the depth-to-water (DTW) index are commonly used to identify areas vulnerable to machine-induced soil damage. However, the applicability and reliability of this approach in non-boreal forestry environments have not been sufficiently evaluated. The objective of this study was to assess the performance of the DTW index as a predictor of soil trafficability in plantation forests outside the boreal context

To address this objective, we examined DTW-based soil trafficability maps across three *Pinus radiata* plantation forests in New Zealand. Skid trails were selected within areas classified as potentially sensitive ($DTW \leq 1$ m) and less sensitive ($DTW > 1$ m). Field measurements included soil moisture content, rut depth, and indicators of soil compaction, specifically bulk density, penetration resistance, and shear resistance. The data were analysed using linear mixed-effects models to account for site-level variability.

The results indicated no significant relationship between the DTW index and soil moisture at the time of sampling. This lack of correlation is likely attributable to temporal differences between harvesting activities and soil measurements, reflecting seasonal variability in soil moisture conditions. Despite this, rutting was consistently more severe in areas with DTW values ≤ 1 m, demonstrating that the DTW index is effective in identifying zones susceptible to surface deformation caused by machine traffic

Overall, the findings indicate that DTW-based trafficability maps are useful for highlighting areas where machine traffic is likely to exacerbate soil disturbance, but they should not be interpreted as defining zones that are entirely resistant or “safe” from impact. While DTW mapping represents a valuable planning tool for reducing logging-related soil damage in New Zealand plantation forests, its predictive capability could be enhanced by incorporating real-time soil moisture information and developing regionally specific flow initiation area (FIA) parameters. Future research should focus on refining DTW-based models to improve their robustness and applicability across a broader range of forest types, climates, and operational conditions.

Keywords: DTM; DTW-index; Soil, Compaction

Mountain spruce forests under disturbance risk: decision support for the spatial prioritization of silvicultural interventions – considering costs and benefits

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Mountain forests often provide protection against gravitational natural hazards and supply multiple ecosystem services but are increasingly vulnerable to climate-change-enhanced disturbances due to legacies of past spruce (*Picea abies* (L.) H. Karst.) promotion. To optimize the allocation of limited operational resources, forest managers must spatially prioritize interventions that balance management costs with timber revenue and forest resistance and resilience ensuring the long-term protective function of these ecosystems.

We present a novel approach for the spatial prioritization of management interventions over a mid-term horizon, considering both silviculture and harvesting operations. We demonstrate the process through a case study area of a Swiss mountain forest. The process includes: (1) a spatial optimization method to delineate operationally coherent forest management units as the basis for prioritization; (2) qualitative and quantitative assessments of silvicultural benefits for forest resistance and resilience under two scenarios with different harvesting intensities (25% and 50% removal of the standing volume); and (3) a quantification of the associated harvesting, planting and thinning costs and of the net revenue for each management scenario.

Our results indicate that the more intense scenario produced a negative net revenue five times higher than that of the less intense scenario. This substantially reduces the area that can be managed given the same limited financial resources. However, the more intense management scenario offered superior silvicultural benefits by reducing mid-term disturbance predisposition and enhancing the overall long-term resistance and resilience. These findings highlight the critical trade-off between maximizing silvicultural benefits for forest resistance and resilience and operating within economic constraints.

Keywords: "Optimization1; Disturbances2; Harvesting3; Silviculture4"

Quantifying boreal forest structure before and after thinning operations using harvester-mounted, drone-based and handheld mobile laser scanning systems

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Harvester-mounted mobile laser scanning (HarvMLS) is a novel approach to quantify forest structure in situ during harvesting operations. However, its reliability relative to established aerial- and ground-based laser scanning systems remains unknown. In this study, we quantified forest structure, assessed structural changes caused by thinning, and benchmarked HarvMLS against drone-based laser scanning (DLS) and handheld mobile laser scanning (HMLS). Point cloud data were collected in a boreal forest in southern Finland during thinning operations in 2024. Forty 10 × 10 m plots were processed using a grid-level approach. Forest structure was characterised using structural attributes (specifically maximum canopy height, mean canopy height, canopy cover (CC) and filled voxel proportion) and the coefficient of variation (CV) of the structural attributes. Results showed that thinning induced consistent structural changes across all three laser systems, which included a minor reduction in maximum canopy height, a moderate decline in mean canopy height, increased canopy openness and reduced filled voxel proportion. Increased CV values across attributes indicated greater heterogeneity post-thinning. No significant differences were observed between the scanning systems in estimating maximum canopy height, mean canopy height, CC or in their associated CV values. While significant differences were detected for filled voxel proportion; post hoc tests indicated no statistically significant difference between HarvMLS and HMLS. All systems consistently estimated the CV value of filled voxel proportion. These results demonstrate that HarvMLS provides reliable estimates of forest structural attributes and their variability during active forest operations.

Keywords: biodiversity; complexity; wood harvesting

Attaining the right bark thickness of pine for the calculation of timber volume using harvester software

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The current development of harvesters and harvesting systems makes it possible to calculate timber volume with a high accuracy, albeit over bark. Despite this, countries where timber is traded based on under-bark measurements, such as Poland, continue to measure volume manually or using photo-optical methods. Meanwhile in Finland, where over-bark measurement is in use, the volume calculated by harvester software can be used in trading. In the end, it is mainly bark or its absence that causes variability in timber volume calculation.

During processing, a certain amount of bark is reduced by the harvester knives, which, as a consequence, artificially lowers the measured diameter and calculated volume. Very careful calibration and accurate measurement of diameter and length does not guarantee that the log volume obtained represents the real volume. This is due to many factors, including season, e.g. in the spring, bark is easily removed or shaved with the harvester head knives, and the system is not able to recognise if the diameter was measured with bark or without bark.

The objective of this research was to find out how much bark is removed during log processing of pine to construct new model of bark thickness that needs to be subtracted when calculating log volume. Initial measurements are being carried out in Winter 2026, where bark thickness has been measured along logs after delimbing, with particular attention to thickness of bark partially removed (under knives) and thickness of natural bark (not shaved). Detailed methods, early data analysis and first results will be presented at the conference in the form of new subtraction of bark thickness for pine, to get close to real timber volume from harvester software.

Keywords: CTL; Bark reduction

Forwarder productivity and fuel consumption in clear cutting, patch cutting and shelterwood establishment

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Mechanized cut-to-length harvest operations with clear cutting as the final operation within the rotation is the predominant harvest method in Fennoscandian forestry. However, interest in continuous-cover-forestry (CCF) methods is increasing. CCF methods such as shelterwoods and patch cuttings can contribute to maintain stand continuity and can provide ecological and social benefits but may also introduce greater operational complexity. Forwarder work in CCF methods is likely to differ from conventional clear cutting due to lower concentration of harvested wood volumes along strip roads and longer extraction distances, but research on the topic is scarce. Therefore, the aim of this study was to determine if forwarder productivity and fuel consumption in fully mechanized shelterwood establishment or checkerboard patch cutting is more time or fuel consuming than in clear cutting, and if so, quantify how much.

The study was conducted on seven harvesting sites in central Sweden, in a block design. Each block contained three treatments: final felling, shelterwood establishment, and patch cutting, covering in total, 9–29 ha, with individual treatment areas ranging from 2.1 to 13.1 ha per block. The patch cuttings were done in a checkerboard pattern over the entire treatment area, in 33 by 33-meters square patches.

Data was collected with the machine control systems as StanForD2010 reports and were collected for each block and treatment area. The reports contained worktime, operator, fuel consumption, driven distance, and forwarded volume. Statistical analysis were done on the work shifts with mixed linear models to predict how time or fuel was explained by meters driven per extracted solid cubic meters under bark (m3sub), treatment and the random effects of operator and block.

Forwarder work in both shelterwood establishment and checkerboard patch cutting required significantly more time and fuel than clear cutting on the same blocks. As a result of different work methods, the mean extraction distance per m3sub in shelterwood establishment was 67 m and not significantly different to the 69 meters per m3sub in clear cutting. In patch cutting, on the other hand, the mean extraction distance was significantly longer (95 meters per m3sub). Based on those mean extraction distances, the patch cutting will consume 26% more time and 27% more fuel while shelterwood establishment will consume 10% more time and 2% more fuel compared in both cases to clear cutting. However, if the methods would be possible to implement with equal driving distances, the study indicates that there would be an 11% increase in forwarding time for both CCF treatments, whereas the fuel consumption would be 2.5% higher in patch cutting and 1.3% higher in shelterwood establishment compared to clear cutting.

These results will be useful when planning shelterwood and patch cutting management, by enabling the differences in fuel and time consumption and, ultimately, costs can be accounted for. Further research could complement the results by further investigating various types of shelterwood removal, patch cuttings of other shapes and sizes, and the total system economy of the management and operations.

Keywords: Harvest-operations; Continuous-cover-forestry; Performance-studies; Forwarder

Predicting forwarder trafficability and rut formation from wheel slip of the preceding harvester

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Rut formation, entailing both a disturbance of soil functions and impaired machine mobility, is a common risk when operating ground-based forest machines under unfavourable soil conditions. As a complement to technical approaches such as flotation tires or bogie tracks as well as planning support tools such as trafficability maps, we present a concept of trafficability prediction for a forwarder building upon measured wheel slip of the preceding harvester. In cut-to-length operations utilizing a wheeled harvester, this machine typically has lower wheel loads than the loaded forwarder which also tends to require a higher number of passes over the machine operating trail. Thus, forwarder traffic commonly contributes more to rut formation than harvester traffic. In our approach, wheel slip data of the harvester combined with accurate position tracing shall be exploited in a prediction model aimed at avoiding severe impact of forwarder traffic on forest soils at locations with sensitive soil conditions. During an initial experiment, a harvester and a forwarder working in sequence were consecutively equipped with a set of sensors for real-time wheel-slip measurement and positioning, and rut depth was measured after machine traffic using a mobile laser scanner. As a work-in-progress report from an ongoing project, the sensor equipment and data processing methods of the concept are outlined, and results from the initial experiment are presented.

Keywords: machines; terramechanics; modelling; low-impact

A Spatial MAUT-Based Assessment of Harvesting System Suitability in Slovakia

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Located in the heart of the Western Carpathian Mountains, Slovakia has a high share of its forest land in mountainous or hilly terrain. In this morphologically and geologically difficult terrain, an adequate harvesting system is required to operate efficiently, prevent environmental degradation and secure forest workers' safety. A large proportion of machinery used in harvesting operations in Slovakia is relatively old. The continuous and still predominant use of tractors in wood extraction causes irreversible erosion, especially on steep and erosion-sensitive flysch slopes, and is also responsible for many accidents. In recent years, their share has been decreasing in favour of more modern and environmentally friendly harvesting systems such as harvesters and forwarders, as well as tower yarders. To support the expansion of innovative and sustainable harvesting systems in Slovakia, this study aims to assess their spatial extent of technical applicability and current application potential in Slovak forests.

The performance of seven state-of-the-art harvesting systems was evaluated for each forest management unit (JPRL) using Multi-Attribute Utility Theory (MAUT) in a spatial GIS-based framework. Terrain-related attributes were derived from a LiDAR-based digital terrain model of Slovakia with a resolution of 1 × 1 m. Other stand-specific data were obtained from forest management plans (PSL). First, the technical compatibility of each harvesting system was modelled based on limiting factors such as slope inclination, obstacle abundance, and skidding distance. However, technical feasibility alone does not ensure sustainable forest operations. To address trade-offs between environmental impacts, worker safety, and economic viability, a MAUT framework was applied. The normalisation of criteria indicator values to a 0–1 dimensionless scale allowed diverse criteria, such as soil disturbance, injury rates, exposure to workplace sickness, and system rentability, to be combined. This resulted in a single evaluation score for each alternative, enabling the suitability comparison of technically feasible harvesting systems within each forest management unit. Scenario-based analyses examined how changes in the relative importance of objectives affect harvesting system modeled suitability and potential application.

The resulting technological compatibility maps of harvesting systems show where each system can be applied and where terrain conditions prevent their use. Complementarily, the harvesting system suitability maps based on sustainability criteria reflect the current potential application of innovative harvesting systems, taking into account both current stand conditions and the relative importance of sustainable forest management objectives for forest managers. The study provides spatially explicit guidance for sustainable harvesting, contributing to the National Forest Programme 2025–2030. Forest district managers and harvesting machinery companies can benefit from this information.

Keywords: sustainable harvesting; GIS; MAUT;

Integration of Mobile Laser Scanning and Biometric Modelling in Single-Tree Volume Prediction

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Accurate single-tree volume estimation is fundamental to forest inventory and operational planning in timber harvesting. Conventional volume estimation relies on field-measured tree dimensions such as diameter at breast height (DBH), tree height, and occasionally upper-stem diameters, which are labour-intensive and costly to acquire at scale. Mobile laser scanning (MLS) offers an efficient means of capturing below-crown stem geometry in boreal forests, yet its potential for supporting volume prediction through integration with biometric models has received limited attention. This study evaluates the feasibility of single-tree volume estimation by combining MLS-derived stem diameter profiles with a semi-parametric taper model. Three MLS measurement configurations of increasing stem coverage were compared on 50 Scots pine (*Pinus sylvestris*) trees in a managed stand in Eastern Finland: (1) MLS-derived DBH only, (2) MLS stem profile from 0 to 2 m, and (3) MLS stem profile from 0 to 5 m. Stem volume was computed by numerical integration of the reconstructed taper curve. Reference volumes were obtained from a taper model calibrated with field-measured DBH, tree height, and upper-stem diameter (d6). As a cross-check, Laasasenaho's three-variable volume equation using the same field inputs was also evaluated.

Volume prediction improved systematically with increasing MLS stem coverage. The DBH-only configuration produced a relative RMSE of 26.1% with a negative bias, indicating that DBH alone provides insufficient geometric information for reliable volume estimation. Extending the MLS profile to 0–2 m reduced relative RMSE to 13.4%, and further extension to 0–5 m achieved a relative RMSE of 10.2%, with 74% of trees predicted within 10% of the reference volume. Laasasenaho's equation showed close agreement with the taper-integrated reference (relative RMSE 5.1%), supporting internal consistency of the field-based benchmark under standard Finnish volume modelling practice. These results demonstrate that MLS-based below-crown stem profiles, when integrated with appropriate biometric models, can yield operationally useful single-tree volume estimates. The approach offers a practical basis for developing efficient ground-LiDAR inventory workflows, with potential applications in pre-harvest assessment and stand-level growing stock estimation.

Keywords: operations; taper; pine; inventory

Seeing the Log in 3D: Automated Volume Estimation of High-Quality Roundwood Using Instance Segmentation

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The accurate measurement of individual, high-quality logs is a critical operational task in the timber trade, particularly during timber auctions where roundwood is traded individually and commands premium prices per cubic meter. In these high-stakes environments, even minor deviations in volume estimation can result in substantial economic losses for either buyers or sellers. Consequently, ensuring accuracy, transparency, traceability, and reproducibility is essential. Currently, log volume estimation predominantly relies on manual measurements using conventional stereometric formulae, such as those of Huber, Smalian, or Newton, in accordance with frameworks like the German Agreement for the raw wood trade. However, these traditional methods are constrained by simplified geometric assumptions, human error, tool calibration issues, and forestry rounding rules. Recent technological advancements in artificial intelligence, image-based methods, and three-dimensional (3D) reconstruction offer a promising pathway to overcome these operational bottlenecks. While small-scale devices equipped with Light Detection and Ranging (LiDAR) or Red Green and Blue (RGB) sensors have demonstrated potential, the integration of these technologies into fully automated, end-to-end workflows for individual log identification and volume estimation remains largely unexplored in operational practice. To address this gap, this study proposes an automated methodological framework that synergizes two-dimensional (2D) instance segmentation based on RGB information with 3D photogrammetric reconstruction, allowing log volumes to be estimated directly from precise geometric models. The proposed workflow comprises four primary stages. First, RGB imagery is acquired using consumer-grade mobile devices (specifically an iPhone 15 Pro and an iPad Pro mounted on a gimbal) providing a flexible, accessible data collection method suitable for auction yards. Second, instance segmentation of individual logs is performed using a YOLOv8-Seg model based on two-dimensional Convolutional Neural Networks (2D CNNs). This strategic use of 2D CNNs robustly isolates logs from complex backgrounds while bypassing the computational heavy lifting and extensive annotation requirements associated with fully 3D deep-learning architectures. Third, the segmented image data undergoes photogrammetric processing to generate detailed 3D virtual reconstructions of each log. Finally, the system automatically calculates the individual log volumes derived directly from the reconstructed 3D geometry. By closely integrating instance segmentation and photogrammetry, this pipeline transitions raw field imagery into highly accurate volume metrics with minimal manual intervention. The practical implications are significant across the forest-wood value chain. For forest owners and auction organizers, it ensures fair valuation and compliance with standardized trading frameworks through transparent, digital documentation. For timber buyers, it mitigates uncertainty and measurement disputes. Ultimately, this methodology reduces operator subjectivity, enhances measurement accuracy, and lays a robust foundation for the future integration of automated digital twins in forest operations and high-value timber trading.

Keywords: Photogrammetry; Instance Segmentation; Roundwood;

Effects of combined-boom-corridor thinning on harvester's operational efficiency and working technique in unmanaged two storied birch dominated stands

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Boom-corridor thinning (BCT) has been proposed as a promising alternative for treatment of dense stands with small-diameter trees, as it promote higher harvester productivity due to effective crane work in comparison to traditional selective thinning (ST). BCT can be performed using high to low degree of systematic approach, from strict (following a strict pattern) to flexible (adjusting the pattern to e.g. stand structures). BCT could also be combined with selective thinning of un-thinned zones in-between boom-corridors (BCTcombo), but which has yet not been studied. The objective was therefore study and compare harvester productivity in BCTcombo and ST in young dense first thinning stands.

The study was performed in North Karelia, Finland in two-storied birch stands. Time studies were executed in 18 study units, to which treatments (BCTcombo and ST) were randomly assigned. The stands were of 8-11 m in height with a mean stem density of 9877 stems/ha (range 2450-16100) of which, on average, 1806 stems/ha (20%) were > 6cm DBH and 80% were below 6 cm DBH, classified as undergrowth. The instructions for the operator were to perform quality thinning and target ca 1500 future crop trees. The harvester used was a Komatsu 901 featured with a 11 m crane and a multi-tree handling harvester head. The trees were harvested at full length or bucked into sections (i.e. tree parts) and bunched along the strip-roads.

Based on the harvester computer data, the harvesting removal for treatment BCTcombo was on average 65 m³/ha and 3333 stems/ha, which was 18% and 13% higher, respectively, compared to ST. The average tree size cut was however 20.5 dm for both treatments. The observed harvester productivity was on average 8.5 m³/PMh for BCTcombo, which was 14% higher compared to ST. Preliminary results from this study aligns well with previous research, showing that that BCT facilitate higher harvester efficiency.

Keywords: biomass; productivity; small-trees; tree-parts

Ground-pressure distribution under a driving forwarder with different tire configurations

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For given wheel loads, the ground pressure exerted by off-road vehicles such as forwarders is to a large extent influenced by tire width and tire inflation pressure. Thus, wide flotation tires, but also flotation bogie tracks, are well-established means of reducing soil disturbance and maintaining machine mobility in forest operations. While reduced tire inflation pressures applicable in forest operations are still higher than those common for agricultural tires during field traffic, there is some development towards lower allowable inflation pressures for forestry tires as an alternative to flotation tracks in certain applications. In this context, the distribution of ground pressure under a driving forwarder was measured with two types of low-pressure tires with nominal section widths of 0.94 m and 0.75 m and with inflation pressures of 1.2 bar and 2.5 bar, as well as with standard tires (nominal section width: 0.71 m; inflation pressure: 5.5 bar) and with flotation bogie tracks (track-plate width: 0.92 m) installed on standard tires. Foil sensors with a spatial resolution of 9.7 mm were used for measurement, and measurements were made for the rear wheels of an eight-wheel forwarder which had wheel loads of 4.5 metric tons. Observed mean and peak ground pressures followed the expected trend and decreased with increasing contact width and decreasing inflation pressure. Thus, observations were consistent not only with previous findings from static measurements of ground-pressure distribution but also with results from field experiments.

Keywords: vehicles; terramechanics; soil; stress

Integration of forest operations in economic assessments of long-term forest growth trajectories

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Forest management faces increasing uncertainty due to climate-driven changes in forest dynamics, disturbances and growing economic constraints on timber harvesting, particularly in mountainous terrain and areas with limited forest accessibility.

For policy implementation and long-term planning, both in government and the timber industry, it is essential to have estimates about the future provision of ecosystem services (such as timber supply or protective service), because harvesting costs strongly determine economic viability of forest operations/forest management.

Most studies to date neglect or greatly simplify operational factors (e.g. by assuming constant net revenues or constant harvesting costs under all conditions). We present a framework that accounts for harvesting costs that vary with harvesting characteristics and terrain properties, supporting long-term forest growth and management modelling. It dynamically assesses best suitable timber harvesting methods (dynBEST) and estimates associated costs under future forest trajectories.

The framework can be integrated modularly with many forest growth and management models to support forest planning.

We will show an example in which the framework is applied to the full Swiss National Forest Inventory network, covering with more than 6,000 plots a broad gradient of biogeographic regions and topographic conditions: We integrate (i) climate-sensitive, long-term forest simulations with the forest model MASSIMO under alternative management strategies, (ii) assessments of technical feasibility of harvesting options, and (iii) productivity-based modelling of harvesting costs over a simulation period of 100 years.

Keywords: Timber_Supply; Forest_Modelling; Ecosystem_Services;

Extraction of Tree Diameter at Breast Height and Height from SLAM LiDAR Data Using an Open-Source Workflow: A Case Study in Eucalyptus Plantations.

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Tree diameter at breast height (DBH) and tree height (H) are essential parameters for monitoring forest growth and estimating carbon sequestration. Conventional field-based measurements are labor-intensive, time-consuming, and costly. In recent years, LiDAR technology has increasingly been applied in forestry due to its efficiency and long-term cost-effectiveness. However, extracting DBH and H from LiDAR-derived point cloud data remains complex, and standardized methodologies are still lacking in Thailand. Furthermore, many existing workflows rely on commercial software, which increases operational costs.

This study proposes an open-source workflow for extracting DBH and H to reduce both cost and processing time. Data were collected in a eucalyptus plantation using a SLAM-based laser scanning system. Two alternative processing approaches were evaluated. The first approach integrates CSF and TreeISO plugins in CloudCompare and the AdQSM software to estimate DBH and H. The second approach employs the 3DFin plugin within CloudCompare. Field measurements were conducted to validate the results obtained from both approaches.

A total of 225 trees were analyzed. The results show that the first approach achieved higher accuracy in estimating DBH, with an R^2 of 0.788, RMSE of 0.726, and MAE of 0.583, compared to the second approach, which yielded an R^2 of 0.541, RMSE of 1.457, and MAE of 1.325. A similar trend was observed for tree height estimation. The first approach produced estimates closer to field measurements, with an R^2 of 0.826, RMSE of 0.824, and MAE of 0.689, whereas the second approach resulted in an R^2 of 0.701, RMSE of 1.055, and MAE of 0.848.

The findings demonstrate that the first approach provides estimates closer to field measurements than the second approach. Additionally, both approaches showed better performance in estimating tree height than DBH. Despite its lower accuracy, the second approach offers advantages in terms of simplicity and reduced processing time. Therefore, each approach presents distinct trade-offs, and the choice of method should depend on user objectives, required accuracy, and resource constraints.

Keywords: ``SLAM_LiDAR; Tree_Attribute; CloudCompare; Open-Source"

Deep learning-based detection of sapwood discolouration in Norway spruce roundwood cross-sections for automated quality assessment in wood supply

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Fungal sapwood discolouration is a major cause of value loss in Norway spruce sawlogs and directly affects grading outcomes according to EN 1927-1. Spores of fungi responsible for sap-stain are naturally widespread in forest ecosystems and spread via insects, wind, rain splash, and contaminated harvesting equipment, increasing the risk of quality loss during log storage.

This study evaluates a supervised deep learning approach for automated detection and quantification of sapwood discolouration in roundwood cross-sections. A dataset comprising 928 images of Norway spruce (*Picea abies* (L.) Karst.) was acquired. Stem discs were placed in a measuring frame and photographed using a digital camera (APS-C format) with a fixed 30 mm focal length lens, mounted on a tripod under varying natural lighting conditions typical of wood yard environments. Discoloured regions were delineated, and the masks distinguished heartwood, non discoloured sapwood, and discoloured sapwood. These masks served as ground truth labels for model training. Images and masks were converted to image resolutions of 128×128, 256×256, and 512×512 pixels, split into training (70%), test (20%), and validation (10%) subsets and augmented by rotations and flipping.

A U-Net was trained for supervised pixel-wise semantic segmentation (discoloured vs. non-discoloured wood). The encoder of the U-Net used convolutional blocks with 16-64 initial filters depending on the image resolution, and downsampling via max pooling. The decoder mirrored the encoder with upsampling and skip connections and a final 1×1 convolution with sigmoid activation produced binary probability masks. Training used the Adam optimizer, and the loss combined binary cross entropy and Dice. Evaluation metrics were the Dice coefficient and the Jaccard index (IoU). Models were trained using a batch size of 30.

Across model configurations Dice coefficients ranged from 0.871 to 0.908 and Jaccard indices from 0.783 to 0.838 on the independent test dataset, demonstrating robust segmentation performance despite heterogeneous illumination and non-standardized camera-to-object distances.

The results indicate that supervised CNN-based image segmentation enables objective, reproducible, and spatially explicit quantification of sapwood discolouration in roundwood. From a forest supply chain management perspective, such methods represent a step toward sensor-assisted quality assessment in harvesting and storage logistics. Integration into mobile camera systems, log-yard scanning setups, or future harvester- or loader-mounted imaging systems could support continuous quality monitoring along the supply chain. This would enable earlier detection of degradation processes, improved storage strategy decisions, and more data-driven timber allocation — contributing to the digitalization and increased transparency of mechanized wood supply systems.

Keywords: log-quality; automated-stain-detection; U-net; sensor-assisted-grading

Precision Modeling of Cut-to-Length Logging Operations for Comparing Thinning Approaches in Finland

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In even-aged young Scots pine (*Pinus sylvestris*) forests, first thinning plays a crucial role in maintaining sustainable carbon sinks. However, forest owners often postpone thinning due to the low operational productivity ($\text{m}^3 \text{E}_h^{-1}$), which reduces profitability and, consequently, contractor and industry interest. To address this sustainability challenge, we modeled boom-corridor thinning with the aim of improving operational efficiency.

The productivity modeling framework was based on workplace-level data and combined time, motion, and principal component analysis. In addition to a traditional tree-level model (RMSE 5.57; MAE 4.30), a workplace-level model was developed to predict productivity and to compare boom-corridor thinning with conventional selective thinning. Productivity differences were primarily explained by a work-motion component, including crane movements, felling and processing activities, stem length, and the number of removed stems. Additional components related to stem size, harvester movement, and supporting work phases (planning, clearing, bunching, and handling of tops and branches) were also identified.

On average, productivity in boom-corridor thinning was 20–25% higher than in selective thinning. Harvester-operator-selected boom-corridor thinning emerged as the only significant predictor of productivity and proved to be the most efficient method. Model evaluation demonstrated improved predictive accuracy (RMSE 3.49–3.52; MAE 2.36–2.45), indicating more reliable productivity estimates.

The proposed modeling framework supports the development of more profitable thinning approaches. Based on these results, harvester-operator-selected boom-corridor thinning can be recommended as a viable method for sustainable forest management in practice.

Keywords: Harvester-operator; Boom-corridor; Productivity; Motion

Comparison of soil compaction and rutting in forwarding and skidding: effect of driving in a curve

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Intensive forestry operations can lead to soil compaction, plastic soil disturbances, and rutting, which negatively impact soils, vegetation, and water bodies. Although many studies have explored the main factors influencing soil damage, it remains unclear whether wood extraction methods and driving direction affect the impacts of forest machinery. Specifically, the differences in soil damage between skidding (SKI) and forwarding (FOR) are not well understood, especially regarding the extent of soil compaction beyond wheel ruts and the influence of driving in curves or in straight lines. This study aimed to compare soil bulk density (BD), soil penetration resistance (PR), and rutting when driving in curves and on straight lines, while considering the total area of soil impacted by wheels and load. The same forest machine (a forwarder) was used during both FOR and SKI to keep machine parameters constant; in FOR, the machine transported logs as an ordinary forwarder, while in SKI, long trunks were fixed with chains to simulate a clambunk. Soil compaction was evaluated using BD and PR in the area impacted by wheel ruts, between the ruts, and by the load outside the wheel ruts. Rutting was quantified using drone imagery and Structure-from-Motion photogrammetry (SfM) to create 3D soil surface reconstruction, allowing for measurement of rut depth and soil volume changes.

In general, both BD and PR increased significantly after 20–25 machine passages on this sandy soil. Across treatments, PR increased by 49–120% within ruts and by 24–71% between ruts, indicating lateral propagation of compaction and a widening of the impacted zone beyond the wheel tracks. When comparing driving straight ahead with driving in a curve at the same transported wood volume (20 FOR and 25 SKI passes), PR within ruts was consistently higher in a curve for both extraction methods (FOR: 3.22 to 4.34 MPa; SKI: 2.82 to 3.85 MPa), and PR between ruts showed the same overall pattern (FOR: 2.45 to 3.07 MPa; SKI: 2.64 to 3.23 MPa). Photogrammetry-derived 3D soil reconstruction further showed that the area affected by the wheel ruts increased in curved segments for both FOR and SKI, and that the total area affected was larger in SKI due to the additional disturbance caused by dragged trunks, resulting in a wider footprint when driving in a curve. Rut depth increased significantly with traffic intensity in FOR; in contrast, in SKI, rut depth estimates were affected by rut concealment, thereby reducing measurement reliability. These results show important information on soil impact, useful for the development of a new wood extraction technique. 3D reconstruction measures soil volume changes and rut depths better than manual measurements.

Keywords: Bulk density; Penetration resistance

Stakeholder-Driven Decision Support for Forest Harvesting Systems Using GIS and Remote Sensing

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Selecting the most appropriate harvesting system is a critical decision in forest operations. In practice, this choice is often based primarily on the experience of forest technicians or logging contractors. Increasingly, however, there is a need for more objective and transparent approaches that can support decisions in complex operational contexts. In recent years, the integration of Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) has emerged as a promising framework for harvesting system selection. This decision is inherently multi-criteria, because operational, topographic, pedological, infrastructural, and stand-related factors all influence system suitability to varying degrees. At the same time, advances in remote sensing and the growing availability of high-resolution spatial datasets, such as Digital Terrain Models (DTM), Digital Surface Models (DSM), and soil trafficability maps, have expanded planning potential beyond the scale of individual stands and toward broader, property-level applications.

Despite this progress, GIS–MCDA planning tools are still not fully integrated into everyday forestry practice, particularly in regions where small-scale and fragmented ownership remains dominant, such as the Italian Apennines. A key challenge in developing a reliable Decision Support System (DSS) for this context is the degree of agreement among stakeholders. Forest technicians, researchers, owners, and logging operators all contribute to harvesting system decisions, but their priorities and perspectives do not always coincide.

To address this issue, we developed a GIS-MCDA-based DSS to identify the most suitable harvesting system at the Forest Management Unit (FMU) level across an entire forest property of approximately 1,000 ha. For each FMU, the DSS selects the most suitable option among three alternatives: forwarder, skidder, and all-terrain cable yarder. The system relies on six criteria that can currently be derived entirely from spatial and remote sensing data, including road network density, distance to the nearest road segment, soil bearing capacity (estimated through soil trafficability mapping), terrain slope and roughness (derived from high-resolution DTM), and harvestable biomass (estimated from DSM data, based on the prescribed silvicultural treatment).

The relative importance of the criteria was determined using the Analytic Hierarchy Process (AHP) through interviews with more than 100 experts representing four stakeholder categories: researchers, forest technicians, forest owners, and logging contractors. The DSS combines spatially explicit criterion values with stakeholder-specific weights to generate suitability maps for each harvesting system. These maps are then overlaid with FMU boundaries to identify the highest-suitability system for each unit. The model was run separately using the weight sets obtained from each stakeholder group, enabling a comparative assessment of agreement and divergence in system selection across the forest supply chain.

Results are currently being finalized and will be presented for the first time at the conference.

Keywords: GIS; LiDAR; MCDA; DTM

Identification methods of strip road trees from hpr data and spatial arrangement of the trees

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Harvester data with accurate GNSS position provides a potentially valuable source of detailed information for forest inventory in first-thinning stands. In thinning operations performed with modern harvesters, all trees along strip roads are removed, forming a systematic line sample that represent approximately 15–20% of the stand. This study investigates how strip road trees can be identified from harvester production file (hpr) data and how strip road placement and within-stand spatial variation affect the estimation of pre-thinning forest attributes. Three different strip road tree identification methods were evaluated using data from seven first-thinning stands in western Finland: (1) a boom angle and length-based method, (2) a buffer-based method using reconstructed strip road centerlines in a global coordinate system, and (3) an angle-only sector method. The accuracy of the resulting diameter distributions, stem counts, and basal area estimates was assessed against detailed field reference data using Reynold's error index and RMSE metrics. In addition, theoretical strip road networks were established and systematically shifted across each stand to quantify within-stand variation and sampling sensitivity. The results show that the buffer-based identification method consistently produced the most accurate estimates, while the angle-only method performed weakest. Offset strip road samples revealed substantial variation in stem count and basal area in some stands, indicating that strip road alignment and spatial heterogeneity can significantly influence representativeness. The findings demonstrate that harvester-based strip road sampling is a feasible and cost-efficient approach for estimating stand-level forest variables in first thinnings, if tree identification methods and spatial biases are carefully considered.

Keywords: harvesterdata, systematic sampling, RTK

Evaluation of Deep Learning Models for Image-Based Classification of Forest Log Assortments by Market Value

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The identification of standing tree species, forest timber assortments, and on-site assessment of their quality and value using images would be widely useful for a variety of applications. In this study, we used the Orange data mining software to classify images of forest wood assortments by tree species and value. The software applies deep learning algorithms for image classification. Our results show high accuracy when classifying assortments by tree species, but lower accuracy when classifying assortments by market value. Classification accuracy for spruce assortment images by market value was only 39.1%. We conclude that further exploration of approaches to classify assortments by value is needed, as this task has the greatest practical significance but currently yields the least reliable results.

Keywords: classification; quality; machine learning

Assessing the effects of the operation planning with precision forestry on the harvesting performances: a case study of CTL logging system in coppice forest

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Forest harvesting operations inevitably affect forest ecosystems, and in order to apply Sustainable Forest Operation a careful planning is essential mainly with high level of mechanization employed. This case study was developed within the framework of the AGRITECH project in one of the first living lab activated. The study area is located in Central Italy in a Turkey oak forest managed as coppice with standards. The area was divided into two plots: an experimental plot, where operations were planned using precision forestry techniques, and a control plot, harvested without preliminary planning, within each plot three replicates were identified. The same harvesting activities were carried out in both plots, CTL logging system, with felling and processing by chainsaw and extraction by forwarder. This research evaluates the feasibility of applying precision forestry to the planning and execution of logging operations in an area typically characterized by rugged terrain and limited permanent extraction roads or tracks. After field data collection, the two treatments were compared using soil surface impacted (percentage of soil affected by the passage of the machinery), working times and productivities and related GHGs emissions and costs. Overall, precision forestry applied during both the planning and operational phases reduced the total impacted surface area by more than 50%, while slightly decreasing working productivity, while there has been only a slight improvement in terms of reduced emissions and costs. These results highlight the good potential of precision forestry to balance productivity, safety, and environmental protection. At the same time, they point to current limitations that, if addressed in the near future, could significantly support the sustainable development of the Italian forestry sector.

Keywords: Logging; SFO; Forwarding; Extraction

Extensive soil disturbance and pronounced biological degradation following mechanized salvage logging after windthrow

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The increasing frequency of severe windstorms in Central European forests has led to extensive salvage logging operations that can have lasting effects on the integrity of the soil and related pedological and biological functioning.

This study quantified the extent and degree of soil disturbance following fully mechanized salvage logging in the University Forest Enterprise near Brno, Czechia, after a windstorm on 21 June 2024. It further explores changes in fine root biomass, root tip density, and mycorrhizal abundances. Five 50 × 50 m experimental plots were established in mature, broadleaf-dominated stands affected by the storm. Salvage logging was conducted in a cut-to-length fashion, and the resulting extent of machine traffic was mapped using high-precision GNSS.

The total disturbed area averaged $28 \pm 3\%$ of the plots when the entire machine operating trail was considered, and $22 \pm 4\%$ when only direct machine–soil contact was included. High-resolution digital elevation models derived from UAV imagery were used to estimate rut depths along 100 randomly distributed transects. Mean rut depth across sites was moderate (0.17 ± 0.11 m), with maximum values reaching 55 cm. Soil bulk density increased by 16% on average (from 1.22 ± 0.22 to 1.38 ± 0.25 g/cm³) in trafficked areas, with site- and depth-specific variations. Besides physical changes, machine traffic also affected biological conditions. Fine root biomass declined by 30%, and substantial reductions were observed for root tip density and mycorrhizal abundances.

Overall, results indicate average degrees of soil disturbance but high related biological impacts, with a striking areal extent—heavily exceeding existing standards and protocols designed for soil protection measures. This study emphasizes the rigorous maintenance of a permanent machine operating trail system, s, even under the unfavorable conditions of salvage logging operations.

Keywords: salvage_logging; soil_disturbance; UAV_photogrammetry; windthrow

Session 2

Comparative Evaluation of Smartphone-Based LiDAR Applications for Tree Diameter Measurement: ForestScanner vs. Arboreal

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Traditional forest measurement techniques which are carried out using calipers and diameter tapes are accurate but they require a lot of manual work in large scale operations. The recent advancements in mobile LiDAR technology which can be installed in consumer-grade devices like smartphones and tablets have introduced new possibilities of quick and remote tree measurement. ForestScanner and Arboreal are two major tree measurement applications based on the in-built LiDAR sensor in Apple devices which are used to approximate the diameter at breast height (DBH) using point cloud-based circle reconstruction techniques. The mathematical comparison of such tree measurement applications in similar field operation environments is still inadequate.

This study compares ForestScanner and Arboreal in the measurement of DBH in natural mixed forest stands at Muratdere Forest Enterprise Chief, Bursa Province, northwestern Turkey. Distribution of natural stands of Scots pine (*Pinus sylvestris* L.) and Uludag fir (*Abies nordmanniana* subsp. *bornmuelleriana* Mattf.) is between the elevations of 871 to 1578 m. Three methods were used to measure 500 trees in 20 sample plots: (1) a traditional diameter tape as a reference, (2) the ForestScanner application and (3) the Arboreal application. To eliminate any variations in hardware, the two mobile LiDAR applications were operated on a similar iPad device with a LiDAR sensor, and the differences observed were due to the software algorithms.

Pearson correlation coefficient, R squared, MAE, RMSE, bias and MAPE will be used to evaluate accuracy. Paired t-test analysis will be used to compare the methods. We also compare the method efficiency by recording the total measurement time per sample plot using each method. Our previous research in this area showed that ForestScanner is highly accurate in DBH estimation ($r = 0.990$, RMSE = 1.49 cm, MAPE = 2.82%) and 65% reduction in time compared to the traditional measurement. The current study extends this work by introducing Arboreal and directly comparing both tools under identical conditions. Particular attention will be given to how application-specific algorithms influence accuracy across tree species, diameter classes, and topographic conditions. The research aims to offer practical guidance to the forestry professionals who would like to integrate mobile LiDAR tools in their measurement process.

Keywords: LiDAR; DBH; ForestScanner; Arboreal

iWOOD: A secure e-auction platform with a digital log profile for transparent trading and more efficient wood processing

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The forestry–wood sector faces a growing need to increase efficiency, transparency, and trust across the supply and processing chain. In roundwood (log) trading, however, a pronounced information asymmetry often persists: buyers make decisions based on limited or non-comparable data on the quality of individual assortments, which increases transaction costs, raises the risk of disputes, and may lead to inefficient utilization of wood raw material. At the same time, pressure is increasing for faster, data-driven decision-making that better links input quality with the economic outcome of processing.

In this context, we present iWOOD—a secure online solution for auction-based log sales, designed to connect modern scanning technologies with an electronic marketplace and an auditable trading process. The key innovation is the integration of 3D log scanning, including CT, enabling the creation of a digital log profile: a data-supported description of selected quality parameters and a visualization (or indication) of internal defects. This profile provides a standardized information basis for comparable bid evaluation and reduces uncertainty in purchasing. From a processing perspective, it also enables improved planning and optimization of operations to maximize yield and product value from available raw material.

iWOOD is conceived as a modular system supporting user registration and role management, creation of auctions with detailed raw material descriptions, and uploading of multimedia (photos, video, 3D/CT data). The result is a clearly defined auction item complemented by a digital log profile that can be selectively disclosed to relevant potential buyers. The platform covers the entire auction workflow—from authentication and authorization, through auction execution and notifications, to bid evaluation and result recording. Strong emphasis is placed on data security and integrity: encrypted communication, two-factor authentication, secure integration with other systems via access tokens, clearly defined user roles, and logging of all key events for traceability and audit.

The platform uses rule-based automated bid evaluation according to predefined criteria and includes analytical tools to support pricing and purchasing decisions. Development is carried out within the LignoSilva Centre of Excellence, which provides both the technological infrastructure (3D/CT scanning) and expert capacity for process digitalization in the sector. The solution builds on a concept validated in a relevant environment and is progressing toward a pilot demonstration under operational conditions with market actors (forest owners, traders, and wood processors). The expected benefits include increased transparency and efficiency in the roundwood market, reduced transactional risks, stronger trust between parties, and a better linkage between raw material quality and processing decisions.

Keywords: e-auction; digital-log-profile; 3D/CT-scanning; market-transparency

Productivity Comparison of Conventional and Crane-Clambunk Skidders under Different Forest Management Systems

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In Mediterranean forest regions such as the Pyrenees, Continuous Cover Forestry (CCF) is widely applied to maintain structural complexity and keep trees standing after harvesting. This approach often requires extraction systems that are flexible, minimally damaging, and capable of operating under variable terrains and stand structures. Among ground-based machines, the skidder is one of the most commonly used timber extraction tools due to its versatility, particularly when equipped with a winch for ground retrieval of stems from uneven terrain.

Traditionally, basic double-drum winch skidders (DDS) have been the dominant machinery in Mediterranean small-scale forests. However, more advanced configurations such as clambunk and crane skidders (CCS) are becoming increasingly adopted due to their higher load capacity and improved efficiency during loading and unloading operations. The literature on Mediterranean logging highlights significant differences in extraction productivity between configurations, and emphasizes the importance of machine type, skid trail conditions, and extraction distance on performance metrics in ground-based systems (e.g., winch vs grapple configurations).

The objective of this study was to compare the productivities of DDS and CCS machines under two forest management scenarios: a final felling in mountain pine stands and a close-to-nature thinning in Scots pine stands. In treatments where the CCS relied exclusively on the crane for loading and used the clambunk for transport, results showed a significant productivity advantage for CCS (6.4 m³/PMH) compared to DDS (4.6 m³/PMH). Conversely, when both skidders operated primarily with the winch – simulating conditions typical of selective or uneven-aged harvests – productivity differences were not statistically significant (3.88 vs. 3.83 m³/PMH for CCS and DDS, respectively).

These findings suggest that in operational contexts where crane-assisted loading is feasible and efficient, clambunk and crane skidders offer a clear productivity advantage over conventional winch-focused skidders. When the extraction context does not allow effective crane use (e.g., dense stands or complex ground conditions), machine productivity converges, reinforcing that operational conditions and silvicultural objectives influence the optimal machinery choice.

Keywords: skidders, productivity, clumbunk, extracting

Hydrological Effects of Forest Road Infrastructure: Evidence from Digital Network Analysis and Scenario Modeling in an Alpine Catchment

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Forest road infrastructure plays a multifunctional role in mountain forest management, with a focus on enabling efficient forest management while potentially altering catchment hydrology and flood response. Despite their importance, the quantitative hydrological effects of forest road networks under varying maintenance conditions are not well understood, which limits evidence-based planning and prioritisation of infrastructure investments. This study combines a comprehensive digital road network assessment with hydrological scenario modelling to quantify the influence of forest road condition and drainage functionality on runoff dynamics in the Rindbach catchment in the Northern Limestone Alps in Austria.

First, the entire network of forest roads accessible to trucks within the catchment area was digitally recorded. Then, selected sections were inspected through systematic on-site surveys. These surveys included a detailed assessment of culverts, the condition of the road surface, longitudinal drainage systems and the load-bearing capacity in both dry and wet conditions. The results revealed significant deficiencies in the infrastructure. For instance, only 59% of culverts were fully functional, while 22% were non-functional and just 18.2% of longitudinal drainage systems were operating at full capacity. However, the load-bearing capacity remained adequate, even in wet conditions (an average of 72.7–73.9 MN/m²), indicating the prevailing geology (limestone). This suggests that weather-related usage restrictions are primarily due to drainage deficiencies rather than structural deficiencies.

Hydrological simulations were then performed using NASIM a deterministic precipitation-runoff simulation tool to evaluate three infrastructure scenarios: (i) the natural state without roads; (ii) the optimal state with fully functional drainage; and (iii) the actual state with documented deficiencies. These simulations were conducted under a 10-year, 12-hour design precipitation of 118 mm. In the sub-catchment areas, peak discharge ($Q_{\max}$) decreased from 8.90 m³/s in the natural state, to 7.50 m³/s with optimal drainage infrastructure, and to 6.80 m³/s in the actual state. This demonstrates that functional drainage systems could act as effective buffers, flattening hydrographs and reducing flashiness indices. Deficient structures prolonged concentration phases and increased baseflow duration through uncontrolled retention effects. These findings challenge the conventional assumption that forest roads universally accelerate runoff, revealing that properly designed and maintained drainage infrastructure could mitigate rather than exacerbate flood risk.

The practical implications emphasize the targeted improvement of culverts and drainage ditches, the strategic closure of little-used roads to restore retention areas, and the implementation of decentralized water retention measures such as retention ditches and infiltration zones. The digital road network provides a solid basis for maintenance planning in line with requirements, hazard assessment, and prioritization of forest road infrastructure investments. This integrated approach demonstrates that hydrologically sensitive forest road planning, combining regular functional monitoring and maintenance with strategic design, improves both operational stability and flood protection at the watershed level in mountainous regions.

Keywords: Runoff; Drainage; Maintenance; Hydrology

Anticipating the impact of climate change on forest operations through educational games

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Forest operations are increasingly exposed to the impacts of climate change. In northern regions such as Quebec, a significant amount of wood is harvested and transported during the winter, when the ground is frozen. These operations are environmentally friendly and less costly. However, climate change is expected to lead to shorter frost periods, prolonged spring thaws, and shifting hydrological patterns. As a result of reduced winter access, dependence on costly summer roads will increase, which will likely disrupt operations, raise costs, and add logistical complexity. The full extent of these disturbances remains uncertain due to the limited predictability of future climate conditions.

The objective of the study was to evaluate the performance of forest operations under various climatic conditions using an educational game, Virtual Wood Supply Arena. Two scenarios were evaluated, representing short and prolonged spring thaws. For each scenario, teams were tasked with fulfilling roundwood demand from mills while taking into account operational limits for harvesting and transport crews.

Under prolonged thaw, transport distances increased even while delivery volumes fell by 8 %. Similarly, roadside inventories increased by 150 %, and costs per cubic metre rose nearly 12 %. It is recommended that the researchers focus on adaptation measures to mitigate these impacts and maintain competitiveness.

Keywords: Educational game; Climate impacts;

Operational UAV imaging and terrestrial LiDAR workflows for reproductive counting and dendrometry in maritime pine, chestnut orchards and hazelnut hedgerows

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Accurate, early and cost-effective field information is a bottleneck for both forest and orchard production systems, especially when decisions depend on reproductive potential and individual tree or hedge structure. The ARGUS consortium develops and validates operational UAV and terrestrial LiDAR workflows to (i) automatically quantify reproductive organs in maritime pine crowns and chestnut orchards, and (ii) estimate dendrometric variables for maritime pine trees and hedge-scale descriptors for hazelnut orchard hedgerows.

For maritime pine flowering, ARGUS implements an end-to-end processing chain from acquisition to indicator delivery. UAV image acquisition was evaluated both with autonomous waypoint missions and targeted crown imaging, and the retained workflow relies on standardized, close-range crown imagery to capture high-resolution images of reproductive organs. A deep-learning detection model, trained with expert annotations and multi-site acquisitions, delivers automated flower counts that are robust, enabling faster, more consistent and scalable estimations. These outputs support monitoring of flowering dynamics and improve decision-making for forest management and seed supply planning. In addition, ARGUS delivers an automated method to detect and quantify chestnut burrs from UAV imagery under variable orchard conditions. The outputs can be produced at orchard and block scales and are directly usable for yield anticipation and operational management.

For dendrometry, terrestrial LiDAR is used to derive structural metrics tailored to each production context. In maritime pine, individual-tree attributes including stem diameter (DBH) and height provide objective phenotyping variables that support genetic selection and evaluation. In hazelnut orchards, hedge-oriented dendrometry (height, width and volume proxies) enables rapid characterization of canopy structure and provides actionable indicators linked to orchard productivity and monitoring.

Keywords: UAVimaging; TerrestrialLiDAR; Deeplearning; Dendrometry

Performance, value, and economics of wood measurement and tracking: a comparison between manual methods and a novel digital ecosystem

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Traditional measurement methods have limitations in data accuracy and compliance with international traceability standards. In the context of forest management and supply chain digitalization, there is a need to develop and test new tools that improve the effectiveness of wood sourcing and tracking. This study evaluated the performance of a digital wood sourcing, tracking, and quality evaluation system developed within the Horizon Europe SINTETIC project. The system integrates Radio Frequency Identification (RFID) of trees and logs, Light Detection and Ranging (LiDAR) for biometric measurement, and acoustic stiffness assessment, all within a client-server digital ecosystem. Two sites were considered based on extraction type: a thinning operation in a spruce-dominated stand and a group shelterwood cut in a mature beech-dominated stand. More than 250 standing trees and 560 logs were surveyed using both manual inventory procedures and the developed digital system. At both sites, detailed measurements were taken regarding biometrics and time consumption for each item; at the second site, digital quality assessment was also included. The data were used to estimate the RFID reading rates, the success of quality assessments, biometric estimate comparisons, and the efficiency and cost of the compared methods. The RFID reading rate was nearly 100%, with only one tag failing due to external factors. The log quality assessment had a success rate of 95%, with failures mainly due to logs with obvious cavities caused by decay. Bias in DBH and tree height was very low, indicating average differences of less than 0.06 cm and 0.4 m, respectively. For logs, differences in volume estimates were less than 0.013 m³. The manual system yielded an efficiency of 0.014 hours per item, while the digital system required 0.020 hours per item (assuming measurements were taken on one tree and four logs sourced from that tree). Within the digital system, tagging added approximately 0.011 hours per item, while tagging and quality checking combined added 0.022 hours per item. Economically, the manual system was estimated to cost 0.37 €/tree, whereas the digital system cost 0.23 €/tree, primarily due to lower labor input. Tagging added 0.24 €/tree, while tagging plus quality assessment added 0.42 €/tree relative to the digital system's base measurement capabilities. These results demonstrate the performance of the digital system which, in addition to lower base costs, provides a fully digital workflow, more precise item-based biometrics, a tamper-proof tracking method, and integrated quality assessments.

Keywords: supply-chain-resiliency¹; cost-reduction²; tracking³; quality-assessment⁴

Productivity and Efficiency of Farm Tractors Equipped with Backhoe Grapples for Extracting Small-Diameter Logs in Thai Short-Rotation Forestry

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Harvesting operations in short-rotation eucalyptus plantations present increasing challenges, particularly when balancing diverse operational practices and performance expectations. Variability in field operations further complicates decision-making, underscoring the need for models that capture realistic productivity dynamics. This study used a simulation-based approach to evaluate how the performance of two commonly used farm tractor modifications—differing in size class and equipped with different types of backhoe grapples—is influenced by payload characteristics and extraction distance in Thailand's very short-cycle eucalyptus plantations. Both tractors (T1 and T2) were monitored using GNSS, from which operational events and travel speeds were derived. Payload size was estimated through manual field measurements. Simulation experiments were then used to quantify how moving speed and payload size affect productivity across a range of extraction distances. Significant differences ($\alpha = 0.05$) in travel speed and payload capacity between the two machines resulted in pronounced disparities in productivity as extraction distance increased. While the number of daily work cycles for both tractors remained similar up to an extraction distance of 100 m, differences emerged in daily production (m^3), productivity (m^3/h), and efficiency (h/m^3), with the larger T1 consistently outperforming T2. At longer distances (e.g., 1000 m), the combined effect of reduced speed and smaller payloads tripled the unit extraction time for T2. These results have important implications for operational planning in Southeast Asian short-rotation forestry. Because these tractors are often used interchangeably in local practice, keeping extraction distances below 50 m minimizes performance variability. At greater distances, T1 maintains notably higher production and a greater number of work cycles, emphasizing the importance of selecting an appropriately sized tractor based on site layout. These tractor modifications were introduced for the first time in international context and presented new sights for small-sized timber extraction performance.

Keywords: performance; models; simulation; plantation

Assessing Forest Operation Impacts on Soil Health: Ecoacoustic Monitoring of Skid Trails and Forest Roads

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Soil compaction caused by forestry machinery poses a significant challenge to the sustainability of forest ecosystems, affecting not only physical soil properties such as pore space and water retention but also biological activity—a key driver of nutrient cycling and soil regeneration. Traditional methods for assessing biological activity are often invasive or labor-intensive. A promising alternative is ecoacoustics, which uses soil microphones and indices like the Acoustic Complexity Index (ACI) to non-invasively and continuously monitor the acoustic activity of soil organisms. This approach offers a way to evaluate soil health and the impacts of different management intensities. This study addresses two central questions: 1. Long-term effects of skid trails: How does machinery traffic during timber harvesting influence biological activity in sandy forest soils, both immediately after compaction and years after last use? and 2. Comparison of forest road types: Do different forest infrastructure types (natural trails, skid trails, forest roads) differ in their impact on acoustically measurable biological activity?

The hypotheses suggest a reduction in biological activity due to compaction (measured via ACI) and differences between road types based on usage intensity and substrate composition. Data collection took place in two study areas within the Schorfheide-Chorin Biosphere Reserve, located in the federal state of Brandenburg, Northeast Germany:

- Skid trails: Acoustic measurements (soil microphones, ACI calculation) and soil physical parameters (density, pH, humus content) were recorded on freshly trafficked and long-unused skid trails.

- Forest road types: Natural trails, skid trails, and forest roads were compared in terms of acoustic complexity (ACI) and microclimatic factors (soil/air temperature, moisture).

Preliminary results reveal no significant differences in acoustic complexity (ACI) between trafficked and untrafficked areas or among road types—despite visually apparent trends (e.g., higher ACI values on skid trails). This raises questions about the sensitivity of the method: While classical soil parameters (density, humus content) responded to compaction, acoustic activity remained largely unaffected. Possible explanations include the overall low biological activity in sandy soils, spatial heterogeneity of soil organisms, limited sample size, or methodological constraints (e.g., sensor sensitivity, noise interference).

However, these findings highlight the potential of ecoacoustic methods as a non-invasive tool for assessing soil health. At the same time, they underscore the need for methodological refinements, which will be included in our further research. In the long term, ecoacoustics could play a bridging role between research and practice, enabling forest managers to monitor the impacts of machinery traffic or infrastructure measures in real time and across large areas—a critical step toward adaptive, soil-conserving management strategies

Keywords: Bioacoustic; SoilCompaction; AcousticComplexityIndex(ACI); SoilBulkDensity

FORAC Harvest Arena – new online training for CTL production management

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Production planning in a Nordic context involves scheduling volumes purchased from private woodlot owners for harvest by independent cut-to-length (CTL) contractors. Planning goals include operational targets for production volume fulfillment, relocation efficiency, and ground damage. The FORAC Harvest Arena provides an online training environment where managers and students can work towards higher goal fulfillment during independent training sessions of varying difficulty.

Each training scenario involves managing 6 CTL teams (harvester, forwarder) towards fulfillment of monthly production goals for 5-7 mill customers over 3 months. 1100 harvesting contracts are located across 3 climate zones where each zone has individual patterns for weekly operating conditions (4 weather classes). The user map interface uses click-and-drag functionality to route harvesting teams between harvesting sites. A 6-factor filter function determines which sites are displayed on the map interface.

The arena offer varying scenarios where the key functionality includes a weekly prognosis for trafficability versus the actual operating conditions met by the manager when the next week arrives. Monthly mill customer demand can be varied in terms for volume and log size. The training typically starts with an informal test-run during stable conditions (mid-summer or mid-winter). It then proceeds to more challenging conditions such as freeze/thaw transitions between ii) autumn-winter and iii) winter-spring-summer.

So far Harvest arena has been used in professional and university training. The primary challenge is high fulfillment of monthly mill production goals (+/- 10 % goal volume per mill customer). In general there has been greater within-group variation for professional training. Even though scenario difficulty increases as training progresses both cohorts increased their production goal fulfillment. Average production scores for professional training increased from 59 to 66 % between autumn- and spring conditions. For university training the scores increased from 77 % for stable conditions to 82% and 87% for autumn- and spring conditions.

Reflections on learning progression: The available selection of harvesting contracts for a single CTL team decreases as demands for site bearing capacity increase and relocation distances decrease. For cohorts with lower levels of production fulfillment, KPIs for both ground damage and relocation efficiency improved with training. However for the final and most challenging scenario (spring) both professional and student groups had similar KPI-levels for ground damage and relocation distances.

Pedagogical approach: Completion of each 12-week training scenario requires 3-4 hours. Each scenario is followed by a post-exercise presentation of results with discussion of i) basic principles and ii) further improvement potential. The follow-up sessions have proved to be particularly valuable opportunity for sharing of practical insights and analytical approaches.

Keywords: training, management, trafficability, on-line

Digital Measurement of Wood Stacks: Evaluating LiDAR and Photo-optical Methods for Volume and Conversion Factor Determination

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Accurate timber measurement is essential for forestry and the wood industry. Lower-value assortments such as pulpwood or energy wood are commonly assessed by manually measuring the gross stack volume and converting it to net volume using conversion factors. These traditional methods are labor-intensive and prone to human error, highlighting the need for fast and objective digital alternatives.

This study evaluates three LiDAR systems (a terrestrial laser scanner (TLS), a personal laser scanner (PLS), and a LiDAR-equipped tablet) and four commercial photo-optical applications (iFovea, LogStackLIDAR, PolterMAX, and Timbeter) for measuring gross volume, net volume, and conversion factors of wood stacks under operational conditions representative of Austrian forestry practice. In total, 22 wood stacks were measured at a timber yard in Austria. Reference net volumes were obtained from electronic 3D log measurements at a sawmill, while reference gross volumes were derived by simulating measurements according to the German roundwood trading framework on high-precision TLS point clouds.

For LiDAR-based measurements, log ends were extracted from the 3D point clouds, rasterized, and analyzed separately for both stack faces. Gross volume was estimated by constructing an alpha-hull around the rasterized log ends to determine the face area and multiplying it by the assortment length. Net volume was calculated from the summed raster area representing solid wood, and also multiplied by log length. The conversion factor was derived as the ratio of net to gross volume.

The LiDAR-equipped tablet showed the highest combined accuracy (RMSE_{gross} = 2.60%; RMSE_{net} = 3.58%; RMSE_{conversion} = 3.33%), outperforming both the photo-optical applications and even the TLS. This result demonstrates that low-cost, consumer-grade LiDAR sensors can provide high measurement precision under practical field conditions. The TLS also produced reliable results, though minor occlusion effects likely reduced its performance in net volume estimation. The PLS delivered accurate gross volume estimates but showed substantial variability in net volume and conversion factor results, mainly due to fluctuations in point cloud density linked to scan duration.

Photo-optical applications achieved high accuracy for gross volume (RMSE_{gross} = 4.73% – 8.78%). However, net volume accuracy varied more (RMSE_{net} = 5.28% – 10.74%). The widely used quadrant method, simulated in this study, showed accuracy comparable to photo-optical approaches but lacked their efficiency and automation advantages.

Regarding field efficiency, photo-optical methods were fastest on average per stack, with Timbeter (0:53 min) and PolterMAX (1:14 min) requiring the least time. The PLS (1:42 min) and LiDAR-equipped tablet (2:39 min) required comparable field times, whereas TLS measurements were substantially slower (6:54 min). Field time variability was particularly high for iFovea and LogStackLIDAR due to occasionally required manual corrections caused by wood stacks in the background.

Overall, the results confirm the strong potential of LiDAR-based approaches for accurate, efficient, and automated wood stack measurement. By enabling reliable estimation of gross volume, net volume, and conversion factors, LiDAR technology can enhance transparency, traceability, and data continuity across the forestry supply chain. The demonstrated performance of the consumer-grade tablet suggests promising opportunities for cost-effective implementation in forestry operations.

Keywords: photo-optical; LiDAR; forestry digitalization

Integrating Tree-Level Quality Attributes into Value-Based Bucking Optimisation

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Value-based bucking is a central optimisation task in cut-to-length harvesting systems, where stem segmentation into assortments determines both product distributions and economic performance.

In Norway, harvester price matrices are typically harmonised within procurement regions, even though considerable variation exists in stem form, internal wood quality, and other tree-level characteristics that influence product value realisation. This study examines how tree-level quality attributes affect optimal bucking decisions and how these shifts propagate along the supply chain under Norwegian operational conditions. Using detailed harvester recorded stem measurements (.hpr) combined with a dynamic programming bucking simulator (OptBuck), we simulated assortment outcomes across multiple scenarios that incorporate variation in wood properties.

Results show that including quality related attributes in bucking optimisation systematically alters assortment composition and net stem value, with pronounced impacts on the proportion and value of sawlogs, being the most economically significant assortment. These changes further influence downstream logistics flows and overall supply chain economics. The findings emphasise the need to integrate tree-level quality information into bucking parameterisation and procurement planning to enhance value capture and operational efficiency in modern forestry.

Keywords: "Tree-bucking; Wood properties; OptBuck"

Time consumption and costs of low removal timber harvesting by use of chainsaw in combination with tractor-mounted processor and grapple loader trailer

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In Sweden, half of the forest area is owned by approximately 300 000 non-industrial private forest (NIPF) owners. While most harvested timber is produced by companies using harvesters and forwarders, NIPF owners still contribute a substantial share of the total time spent on forest work. A large part of this work concerns logging, where tractor-based equipment, using chainsaws, tractor-mounted processors, and grapple loader trailers, represent a low-investment alternative for small-scale logging operations. Additionally, this equipment may be economically feasible for low-removal harvesting. However, studies on tractor-mounted processors' work performance have been limited in recent decades, resulting in a lack of updated data on time consumption and cost estimates. Additionally, to the authors' knowledge, no previous study has evaluated the combined tractor-based system during low-removal harvesting.

To address this knowledge gap, time studies were conducted in Southern Sweden during a low-removal harvest operation with a removal intensity of 10%. The studied system consisted of a Husqvarna 550 XP G chainsaw, a Hypro 450 XL processor, and a 101 4WD FTG Moheda grapple loader trailer, where the processor and grapple loader trailer were attached to a Valtra A105 tractor. The same operator executed all work in the study. Based on the time study data, regression models were developed that explained time consumption for work elements, and machine costs were estimated using the COST model.

In total, the studied logging operation comprised 36.2 productive machine hours excluding delays (PMH₀). Data was collected for 157 trees for chainsaw work and 161 trees for processor work, where the discrepancy was caused by equipment errors. Mean diameter at breast height (DBH) was 23.4 cm. For forwarding, 12 loads were recorded with a mean forwarding distance of 1 260 m and a mean load volume of 6.6 m³ob. Observed productivities for the chainsaw, processor, and grapple loader trailer work were 8.7, 4.3, and 6.3 m³ob PMH₀⁻¹, respectively. Costs, when excluding wages, were 0.26, 11.61, and 6.88 € m³ob⁻¹ for the chainsaw, processor, and grapple loader trailer work.

For chainsaw work, inter-tree distance, DBH, manual bucking, and tree species had a significant effect on time consumption. For processor work, distance between tractor stops, winching distance, DBH, manual bucking, and tree species were significant predictors. For the grapple loader trailer, forwarding distance and load volume significantly affected time consumption. Overall, the resulting models showed clear and strong relationships between predictors and time consumption and provide updated data for evaluating tractor-based harvesting systems. However, caution is warranted as the study was based on the observations of a single operator.

Keywords: felling; processing; harvesting; forwarding

From failure to resilience: Assessing the performance forest road drainage systems under extreme precipitation

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Forest roads are a critical component of forest management infrastructure. They ensure access to timber resources but may also support recreation, conservation and access to rural areas. In Norway, extreme precipitation events have lately caused widespread road failures and erosion and have highlighted limitations in existing drainage design standards. This study presents final results from an integrated assessment of forest road drainage performance under extreme rainfall conditions with respect to culvert design, density and placement.

We chose two case study areas heavily affected by extreme precipitation events in recent years to study the efficiency of current design standards under present and future climate conditions. We combined detailed field surveys with digital terrain data to model flow paths, estimate surface runoff and evaluate the hydraulic performance of existing drainage structures for different return periods and under climate-adjusted precipitation scenarios. These analyses were complemented by cost–benefit assessments to quantify the relationship between drainage capacity, infrastructure damage, and investment costs.

The results indicate that minimum design standards based on 25–50-year return periods are often insufficient under current and projected climate conditions, particularly in steep terrain. Culvert capacity, inlet and outlet configuration, road alignment, and longitudinal slope were identified as key factors influencing failure risk. The study further demonstrates that targeted upgrades of critical drainage elements, including increased culvert dimensions and improved inlet protection, can substantially reduce damage while remaining economically viable.

Based on the empirical findings and model simulations, the project delivers updated, evidence-based recommendations for forest road drainage design, upgrading, and maintenance. A practical risk assessment framework and a spreadsheet-based decision-support tool for culvert dimensioning were developed and validated in the study areas. These tools enable forest road planners and managers to identify vulnerable sections, prioritize interventions, and balance technical performance with economic constraints.

By integrating field observations, hydrological modelling, and economic analysis, this research provides concrete guidance for improving the resilience of forest road networks under increasing climate variability. The outcomes support adaptive infrastructure planning and contribute to strengthening sustainable and resilient forest value chains.

Keywords: Forestroads; Precipitation; Culverts; Resilience

FORECASTING SOLUTIONS FOR CHARACTERIZING LOGGING CONDITIONS AND SUITABLE WEATHER CONDITIONS USING SATELLITE DATA

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Annual logging planning with optimization solutions relies on measurable criteria for felling area conditions and suitable weather. Increased data precision improves the reliability of the optimization assessing logging feasibility and simulates the effects of varying weather scenarios. Which leads to effective process management by centralizing planning of harvesting. The study aimed to improve the precision of regression-based forecasting models predicting logging conditions through the integration of satellite data with previously used meteorological center inputs, leveraging the satellite data's higher spatial resolution, better spatial coverage and spatial variability detection of the satellite data. Secondly, geospatial information system (LVM GEO) data was integrated with meteorological measurements, implementing finer special data (10X10km) improving the precision of area-specific forecasts. The study was realized on data of 12000 final fellings and 5000 commercial-thinning of JSC "Latvijas valsts meži" (Latvia's State Forests) from year 2017 to 2024. For each felling area were assigned points that characterize the proportion of bad and extreme logging conditions from total cutting volume in the last 7 days in each company region. The 7-day average of adverse logging conditions correlated best with weather constraints. Felling areas were additionally characterized by felling volume combined with the proportion of the area with groundwater levels up (according to the LVM groundwater model), and the distinct impacts of each forest type. Furthermore, for each felling area, satellite-derived temperature and precipitation data over 7-, 15-, and 30-day periods during logging obtained from ERA5 and Copernicus repositories, were analyzed in parallel with measurements from 26 Latvian State Geological and Meteorological Center weather stations. Further a regression analysis was performed to develop a predictive model for assessing logging conditions and assigning "points" (lower points – easier logging, higher points – harder logging) of each felling area. Geospatial information system data that has proven to be significant ($p < 0.05$) is the proportion of the felling area where the groundwater level reaches up to 0.1 m in combination with the felling volume in addition to forest types ($p < 0.05$). By regression analysis the weather condition impact on logging possibilities was set. Equation allows to calculate the maximum logging points under defined weather constraints. Satellite data that has proven to be significant ($p < 0.05$) are daily maximum air temperature at 2 m height, daily minimum air temperature at 2 m height, daily mean air temperature at 2 m height, soil moisture at depth, soil moisture index, precipitation sum, snow depth, soil temperature at depth. The additional factors allowed to increase the coefficient of determination by 1% on average for the felling data equation, and by 8.5% on average for the weather conditioning equation. As a result, using seven years of weather data, three meteorological scenarios—optimal, moderate, and suboptimal for logging—were defined per region. Monthly 15- and 30-day average temperatures and 30-day precipitation were used to calculate logging condition indices via two predictive models contained in information system and optimization system providing objective criteria to identify the most suitable month for harvesting each area.

Keywords: forecasting; logging; satellite; efficiency

Non-contact Length Measurement in Forest Harvester and Processor Heads

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Forestry operations are under growing pressure to supply sawlogs as quickly, cost-effectively and customer-specifically as possible. In fully and highly mechanised timber harvesting systems, harvesters and processors take on a key role at the front end of the wood supply chain, as they determine the assortment lengths directly in the machine. The commonly used length measurement systems rely on a tactile measuring wheel that is pressed against the trunk during feed. However, under the extreme operating conditions, these systems are increasingly reaching their technical and methodological limits.

The current measuring principle records the distance travelled along the log surface, which corresponds to the shortest end-to-end connection only in the ideal case. In addition, variable contact conditions affect the measurement: contact pressure, wood and bark properties as well as weather conditions (wetness, ice, temperature) change the effective rolling circumference. Furthermore, slippage, missing bark, branches and branch stubs can interrupt continuous contact with the log surface and lead to measurement errors.

In practice, machine manufacturers therefore prescribe regular manual calibrations, often several times per day, to detect and reduce systematic deviations. This additional step, however, reduces productivity, is itself prone to errors and has little effect on the variation of the measured data. To reliably meet the required minimum length and avoid the risk of quality downgrades due to undersized lengths, additional overlength is therefore often applied. This results in an economic loss of value for forest owners, as sawmills usually only pay for the required nominal length.

Within this context, a systematic literature review is being conducted to examine the current state of research on non-contact alternatives for length measurement in harvester and processor heads. The aim is to identify existing approaches, compile and compare them and thereby develop a clear insight into the challenges and potential of individual measurement methods in view of the extreme operating conditions in timber harvesting.

Alternative contactless measurement methods have been investigated since the early 2000s. Optical approaches are considered promising, as are methods using microwave or laser technology. Key limitations are interference from contamination, vibration and occlusion. At the same time, advances in sensing technologies and analysis algorithms are expected to further increase measurement accuracy and robustness. In light of these findings, subsequent research will focus on developing and evaluating a novel, non-contact, multi-sensor system to achieve more precise, calibration-independent length measurements.

Keywords: Harvester; Length-measurement; Calibration; Non-contact-measurement

Reed–Solomon–Based symbol encoding for robust sawlog traceability

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Reliable end to end traceability of individual sawlogs from the forest to the sawmill is a key enabler for digitalisation, process optimisation, and value recovery in the forest value chain. Code based log identification using computer vision offers a scalable alternative to physical tagging, but its practical deployment is challenged by variable visual conditions, partial occlusions, and classification uncertainty typical of forest and industrial environments. This study investigates the robustness of Reed–Solomon–based symbol encoding for code based sawlog identification under realistic detection and classification noise.

We present a simulation based evaluation of a computer-vision classifier system using an Reed–Solomon RS(8,4) symbol code to encode log identifiers. The code consists of four data symbols and four parity symbols, providing a minimum Hamming distance of five and enabling correction of multiple symbol errors or erasures. To emulate realistic classifier behaviour, synthetic confidence matrices are generated by jointly modelling per symbol detection probability and inter class discriminative power. This framework enables controlled analysis of identification performance across a wide range of noise levels, symbol loss rates, and dictionary sizes, up to the full RS code space of 23^4 possible identifiers.

Code recovery performance is evaluated using both hard decision decoding, which selects the most likely symbol at each position, and soft decision decoding, which exploits the full confidence distribution across symbol candidates. Results show that soft decision decoding consistently and substantially outperforms hard decoding across all tested scenarios. In low noise conditions, correct identification rates exceeding 99% are achieved even for per symbol detection probabilities as low as 0.8, without applying any dictionary constraints.

Under moderate noise, identification rates above 98% are maintained for dictionary sizes of up to 20 000 identifiers, demonstrating strong scalability for industrial scale deployments. At high classification noise levels, and symbol detection probabilities as low as 50%, performance becomes increasingly dependent on both code design and dictionary filtering. Here, 74% of identifiers are correctly recovered using dictionary-constrained decoding, primarily due to the strong minimum distance properties of the RS(8,4) code. This performance is primarily attributable to the code's minimum Hamming distance of five, which guarantees unambiguous recovery in the presence of up to four missing or erroneous symbols. Notably, even when more than four symbols are missing or misclassified, the dictionary-constrained decoder frequently identifies the correct code candidate, highlighting the benefit of combining error correcting code structure with probabilistic decoding.

Overall, the results demonstrate that Reed–Solomon–based symbol encoding, combined with soft decision decoding and optional dictionary constraints, enables robust and scalable code based sawlog traceability under challenging visual conditions. The proposed approach supports reliable digital identification of individual logs in forest and sawmill environments without reliance on physical tags or manual intervention.

Keywords: forest digitalization; computer-vision; deep-learning

Preliminary studies on the effects of timber skidding using a battery-powered micro-skidder

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The aim of the study was to characterise the effects of timber skidding using a prototype battery-powered Salamander 600 4×4 micro-skidder and the impact of this operation on the topsoil layers along the skid trail. The tests were carried out in a young oak stand growing in a mountain broadleaved forest habitat, on sloping terrain with an average slope of 15° (26-27%) and numerous obstacles in the form of stones.

The timber was skidded in two stages. In the first stage, the long logs were pulled individually from the cutting area towards the skid trail. The average distance of timber transport in this stage was 42 m (39-44 m). Then, each load was transported along a 70-metre trail to a storage site by the forest road, where short assortments (bolts) were cut and loaded onto a transport vehicle. The slope gradient in the cutting area was 13° (23%), and on the trail in the longitudinal direction it was 9° (16%). On the skid trail surface, there were many boulders protruding from the ground and several transverse depressions, which effectively limited the speed of the micro-skidder both with and without a load.

During the work, continuous time measurements were performed using the Timing 1.1 application. The application allows the duration of all observed activities to be recorded with an accuracy of 1 second. The duration of each successive observed operation and delays were recorded in a PSION Workabout MX portable field recorder. Before the observation began, the length and diameters of the logs were measured. The Huber formula was used to calculate their volume. The operator had two years of experience both in forestry operations and in operating micro-skidder.

Soil parameters were measured after the first and tenth skidding cycles on three transects perpendicular to the trail axis, located at the beginning, middle and end of the trail. Within each transect, at five points (in ruts, between ruts and at a distance of 1 m from ruts on both sides of the trail), soil compactness was measured with a FieldScope SC 900 static penetrometer, and soil moisture and conductivity were measured with a Spectrum Technologies TDR 350 meter. In addition, soil samples were taken to determine bulk density and moisture content under laboratory conditions.

The average volume of a single load was 0.16 m³ (0.10–0.27 m³). The time required for skidding in productive work time, in the first stage over the described distance within the cutting area, amounted to over 22 min/m³, while the time required for skidding along the trail amounted to over 24 min/m³. The micro-skidder operator needed a total of 47 minutes to skid 1 m³ of timber over an average distance of 112 m. The skidding efficiency in the first stage was 2.89 m³/h and was about 13% higher than the skidding efficiency along the skid trail. A statistically significant increase in soil compactness occurred on the trail in ruts at a depth of up to 20 cm. Changes in other parameters proved to be statistically insignificant.

Keywords: small-scale mechanization; productivity; soil

The use of photo-optical measurement of wood raw material - experiences from the State Forests National Forest Holding in Poland

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The accuracy of round wood volume determination is fundamental to planning and accounting for individual processes in the wood trade. The rapid technological development of mobile devices, including computers, digital cameras, and automated systems, has enabled the emergence of practical data acquisition tools. This also applies to various areas of forest management. One option in this regard is the measurement of wood raw material using photo-optical techniques.

The functioning of the different applications is quite similar and proceeds in the following phases:

1. Taking a series of images of a stack of medium or large-sized round wood.
2. Merging of the images into one panoramic image.
3. Analysis of the panoramic image in order to:
4. Identification of the cross-cut forehead of round wood and counting them,
5. Inscribing circles in the cross-cut forehead sections,
6. Making a diameter distribution table,
7. Inscribing the pile into the polygon and calculating the area of the polygon,
8. Determination of the replacement coefficient from the ratio of the area of the cross-cut foreheads of wood to the area of the polygon, or use of a preset coefficient.
9. Calculation of the stack volume and preparation of the report.

The State Forests had its first experience with photo-optical measurement of wood raw material between 2013 and 2015, commissioning a research project for the SF Development and Implementation Centre in Bedoń. Three applications were analyzed: iFOVEA by FOVEA GmbH, AFoRS by Scheller Systemtechnik GmbH, and sScale by Dralle A/S. Approximately 25,000 m³ of stacked wood were measured. Compared to the volume obtained from manual measurement, the values for the individual methods were -0.58%, +2.17%, and +4.07%, respectively, and the labor intensity ratio was 1:0.47:0.63:0.23. Later, only the sScale application was used more widely, measuring approximately 1.6 million m³ of stacked wood from post-hurricane areas in 2017-2018. In 2020, tests with the Timbeter application began. In 2024-2025, as part of the second phase of implementing photo-optical roundwood measurement, this application was deployed in over 100 forest districts (primarily in the Piła and Poznań regional directorates). Test results indicated that the application provides sufficient quality results and the required accuracy compared to the traditional reference. It enables seamless data transfer to the State Forests' IT system. As of October 2025, approximately 650 forest districts are using this application in production.

Keywords: smartfone application; wood measurement

CastaneaGPT: Designing a Domain-Specific RAG-Based Assistant for European Sweet Chestnut Management

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The application of large language models (LLMs) in forestry is still experimental to large extent, specifically in highly specialized subdomains such as the European castaniculture. This scientific initiative presents CastaneaGPT, a domain-specific digital assistant which is designed to support sweet chestnut (*Castanea sativa*) management in Italy and beyond. CastaneaGPT is conceived as both a working prototype and a methodological case study, and aims to illustrate how a professional AI system can be developed within a forestry context.

The system follows a modular architecture with a clear separation between backend “reasoning” and frontend presentation. The backend is based on a Retrieval-Augmented Generation (RAG) pipeline that combines OpenAI LLM models with LlamaIndex for document ingestion, indexing, and retrieval. The integrated text corpus includes curated scientific literature, grey literature, and web-based materials, processed through structured PDF and URL ingestion workflows with metadata extraction and citation control. Upgrade measures such as enhanced retrieval strategies (e.g., MMR, hybrid BM25), chunk-size optimization, conversation memory, and a forestry-related glossary are implemented to consolidate the factual grounding of the tool. FastAPI serves as the orchestration layer, enabling containerized deployment (Docker) and flexible frontend integration (e.g., Glide). The user interface is planned to integrate three main features: dashboard, map (PostGIS-based), and chat components.

Beyond the technical realization, the project is driven by two principal scientific interests: (1) the methodological challenges in building a reliable forestry-specific RAG corpus, and (2) the empirical testing and evaluation of different interaction modes between user and AI assistant (e.g. for professional castaniculturalists; seekers of decision support when reactivating abandoned chestnut plantations; playful users such as children) in order to evaluate the influence of these interaction modes on the comprehension and the trust of the users.

CastaneaGPT is conceived as a digital platform to connect the castanicultural community, support decision-making, and strengthen knowledge dissemination, while offering a reproducible blueprint for similar domain-specific AI tools in forestry.

Keywords: Digital_Forestry; CastaneaGPT; LLMs; Decision_Support

CTL operations with biomass piling may be more expensive than harvesting with regular biomass distribution

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Utilising biomass (tree branches and treetops) for energy purposes is a common practice in mechanised forest operations. Collecting biomass, however, may be time consuming if, for easy and effective forwarding, the harvester operator is focussed only on timber piling, but not paying attention to biomass piling. To make biomass forwarding more effective, placing it in piles is an alternative that can boost productivity in the last stage of forest operations: biomass extraction. The objective of this research was to compare the productivity and costs of cut-to-length (CTL) technology in two types of forest operations: with biomass piling (WBP) and with no biomass piling (NBP), while the timber processing in both cases was the same.

The research was carried out in North-West Poland in a pure, 96-y.o. pine (*Pinus sylvestris* L.) stand, in which clear cutting was applied on an area of 3.33 ha (half WBP and half NBP). A John Deere 1170E harvester and John Deere 1110E forwarder were used, with the forwarder also extracting the remaining biomass. In the WBP and NBP operations, the timber was piled next to the strip roads as usual. However, in WBP, the biomass was placed in piles next to the strip roads (there were empty spaces between each pile), while in NBP, the biomass was equally and continuously distributed along the strip roads.

The productivity (m³ PMH0-1) of timber harvesting and forwarding in WBP was 14% lower in comparison with NBP, while the biomass extraction was 34% higher in WBP than in NBP. Specifically, the productivity (m³ PMH0-1) of the harvester in WBP vs NBP was 18.75 vs 21.32; the productivity of the forwarder was 18.58 vs 21.17; and biomass extraction was 7.37 vs 5.52 (34% more in WBP).

The total costs of timber harvesting, as well as timber and biomass forwarding (weighted arithmetic mean) was 8.84 € m⁻³ in WBP and 7.88 € m⁻³ in NBP (thus WBP was 12% more expensive). However, the cost of biomass forwarding only was lower by 33% in WBP (9.19 € m⁻³) in comparison with NBP (12.18 € m⁻³).

Keywords: Harvester; Forwarder; Treetops, Branches

Session 3

ForestFusionNet: A Unified Deep Learning Framework for Multimodal Tree Species Classification in Young Boreal Forests

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Accurate tree species identification in young boreal forests is critical for sustainable forest management, biodiversity monitoring, and bioenergy resource assessment. However, current remote sensing approaches predominantly rely on single-sensor methodologies, limiting classification accuracy in complex young stands where trees exhibit similar heights, small crowns, and subtle spectral differences.

This research aims to develop and validate ForestFusionNet, a scalable multimodal deep-learning framework that fuses LiDAR-derived 3D structure, high-resolution digital aerial photogrammetry (DAP), Sentinel-2 multispectral time series, and Planet high-resolution multi-temporal imagery to classify tree species at the individual-tree level in young boreal forests. The work pursues two main objectives: (1) to build a harmonized multi-sensor dataset and extract complementary features, and (2) to design a unified fusion deep-learning architecture and rigorously evaluate its accuracy and computational efficiency.

The study will be conducted in two young boreal forest sites in Juva (27.865E, 61.730N) and Heinävesi (28.736E, 62.509N), Finland. The proposed ForestFusionNet architecture will employ sensor-specific encoders: a point-cloud network for LiDAR and a CNN for aerial imagery.

The proposed ForestFusionNet architecture will utilize sensor-specific encoders, including a point-cloud network for LiDAR, a CNN for aerial imagery, and a temporal module for satellite time series. Different fusion mechanisms (late, intermediate, and deep) will be explored to combine modalities optimally. The model will be trained and validated using field-collected individual-tree reference data. The model's performance will be compared with single-sensor results by evaluating how well it identifies each species using metrics such as precision, recall, F1-score, and overall accuracy. Ablation studies will quantify the contribution of each modality, and computational costs (training/ inference time, memory usage) will be reported to assess deployability for large-area mapping.

We anticipate that ForestFusionNet will achieve significantly higher classification accuracy compared to any single-sensor approach by leveraging the complementary strengths of 3D structure, high-resolution texture, and phenological spectral patterns. The project will deliver (i) an open-access harmonized multi-sensor dataset hosted on Zenodo; (ii) the complete ForestFusionNet code released on GitHub; (iii) empirical evidence on the accuracy-efficiency trade-offs of multi-sensor fusion; and (iv) a scalable operational framework for precision inventory of young boreal forests.

The results will directly benefit forest owners, small- and medium-sized enterprises, and policymakers by enabling cost-efficient, high-precision forest inventory. Moreover, improved individual-tree species information will support more reliable biomass and carbon stock estimates, thereby enhancing national and EU climate reporting under the LULUCF sector and supporting the targets of the European Green Deal.

Keywords: Deep learning, multimodal fusion, tree species classification, young boreal forests, remote sensing

Keywords: Deeplearning; fusion; classification; forestry

Process Analysis for Semi-Autonomous Reforestation Operations with Autonomous Mobile Robots

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Ongoing climate change and associated damaging events are leading to a significant need for large-scale forest regeneration. The key challenge is to efficiently address the increasing demand for reforestation despite a shortage of skilled workers by means of automated processes. In Germany, reforestation is still predominantly carried out manually and is associated with high labour intensity. First planting machines as well as excavator-based planting attachments are available; however, due to limited productivity, their adoption in operational practice remains low. In parallel, approaches for drone-based seeding are being explored, but these currently achieve only limited establishment success due to insufficient soil contact and the lack of precise positioning.

The establishment of the next tree generation represents the starting point of resilient forest value chains. Here planting operations are of central importance. Automated and digitally supported planting systems offer the potential to perform this key task more efficient, reproducible, and less labour-intensive.

Against this background, the ForestBots research project, funded by the German Federal Ministry for Research, Technology and Space within the funding initiative “Digital GreenTech – Environmental Technology Meets Robotics” (FKZ: 02WDG1760A), addresses the development of a collaborative system for automated reforestation. The objective of the project is to demonstrate a semi-autonomous forest operation using a small swarm of fully electric tracked vehicles for seedling planting.

This contribution focuses on the systematic analysis of the process chain as a foundation for the development of automated and digital planting systems based on autonomous mobile robots (AMR). The requirements for an automated planting process were derived based on a comprehensive analysis of the state of research and technology, a patent and market review, as well as expert interviews and workshops with forest nurseries and forestry stakeholders, including the Lower Saxony State Forests and the Chamber of Agriculture. These include, among others, seedling characteristics, operational timing, and relevant environmental and site conditions.

Based on this, the overall process of seedling planting was broken down into its essential functional subprocesses. These include system coordination at the global level, seedling handling and logistics, as well as a detailed analysis of the planting process itself. For each subprocess, dependencies, interfaces, and critical tasks with particular relevance for automation were identified.

The results provide a structured description of functions and processes as a basis for further concept development and for the integration of sensors, actuators, and data-driven decision-making. The study thus contributes to the development of robust, semi-autonomous, and digitally connected systems for reforestation.

Keywords: reforestation; autonomous; robots; planting

A new high-tech low-cost light yarder for small-scale forestry

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In 2026, an Italian machine manufacturer developed a new light yarder designed to match the specifications drafted in 2024-2025 by CNR, through a survey of small-scale logging contractor preferences (presented at FORMEC 2025). That study stressed the importance of practicality and low cost, and directed design efforts towards a lightweight, compact machine that can cope with poor infrastructure (narrow landings) and can be moved with a pickup truck. At the same time, the machine must present innovative characteristics, in order to compete with other small-scale yarders and qualify for public support. The result was an extremely light tower yarder, powered by an Otto-cycle engine, which is light, efficient and exempt from many of the regulatory limitations imposed on diesel engines. The new yarder features an electric carriage weighing only 60 kg (including 30 m of 8 mm cable), but capable of carrying a 1000 kg load. To maximize operational flexibility and convenience, the machine is a three-cable all-terrain type and is equipped with its own folding tower. Operation is obtained through a modern remote control. The proposed presentation will offer a detailed description of the machine and of the results from the first field trials, conducted in 2026.

Keywords: Yarder; Cable; Mountain; Electric

Carbon Footprint Assessment of Teak Plantation Management under the Thai Silvicultural Regime

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Greenhouse gas emissions from forest management operations are currently gaining global attention for tackling climate change by reducing the carbon footprint of forestry activities. This study aimed to quantify the carbon footprint of a full rotation teak (*Tectona grandis*) plantation, identifying key emission sources in silviculture and harvesting. This study assessed the carbon footprint of teak plantation management in the Mae-Moh Forest Plantation, Lampang Province, Thailand, over a 30-year period. The analysis consisted of two major components: silvicultural practices and harvesting operations. The life-cycle emissions of carbon dioxide from silvicultural practices were estimated at 1726.5 kg CO₂eq ha⁻¹, with annual firebreak construction 1176.0 kg CO₂eq ha⁻¹ and followed by fertilizer application accounting at 338.0 kg CO₂eq ha⁻¹. The first year of establishment generated the highest emissions owing to the implementation of all silvicultural activities. Harvesting operations resulted in 14.2 kg CO₂eq/m³ in final felling, with short-distance transportation identified as the largest contributor (5.3 kg CO₂eq/m³). When aggregated over the full rotation, the 15th year exhibited a peak in annual emissions associated with plantation management. Potential mitigation strategies include optimizing machinery size and operation, implementing regular equipment maintenance, and applying fertilizers according to the soil nutrient status and plant-specific demand. Therefore, an integrated nutrient management system that emphasizes organic amendments is recommended to reduce the carbon footprint of teak plantations.

Keywords: "Consumption; GHGs; LCA; efficiency"

Energy consumption and greenhouse gas emissions of liquefied biogas (LBG)-powered heavy-duty woodchip trucks in Finland: Preliminary results

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Globally, road transportation is a major source of greenhouse gas (GHG) emissions. One possible option to lower GHG emissions of road transportation is to use alternative fuels, for instance liquefied biogas (LBG) and electricity, on vehicles. During recent years, LBG-powered trucks have grown in number even on the road transportation of the forest sector, such as timber trucks and woodchip trucks. In this study, we utilized a holistic approach to consider all possible impacting variables to explain energy consumption and further GHG emissions.

Dataset consisted of vehicle information from seven heavy-duty (gross vehicle weight of 75 tonnes) woodchip truck combinations. Three of the trucks were LBG-powered and rest were diesel-powered vehicles (references). Additionally, multiple different data sources (i.e., weather information, route properties and driver-related variables) were included in the study. The dataset had 7310 payloads and the total mileage of the vehicles during the study was over 1.3 million kilometers.

According to our preliminary results, on transportation cycle, including 100 km empty driving, loading payload, 100 km laden driving and unloading payload, the LBG combinations used 6% more energy compared to the diesel vehicles when a measurement of MJ tkm⁻¹ was applied. However, the LBG combinations had 60% lower emissions (g CO₂eq. tkm⁻¹) compared to the diesel vehicles when the default emission factors of the ISO 14083:2023 standard were utilized.

Moreover, the variables affecting energy consumption were detected. From weather variables rain occurrence, ambient temperature and snow cover accumulation on the road had statistically significant influence on energy consumption. Furthermore, from road properties, mean grade between starting and ending points of the trip and elevation variation during the route affected energy consumption. Respectively from driver-related variables, time since the driver has completed eco-driving course for Driver Certificate of Professional Competence renewal influenced energy consumption.

Keywords: Alternative fuels; Holistic approach

Automated Assessment of Harvesting Quality Using Machine and Point-Cloud Data in Thinning Stands

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In Finland, thinning operations are carried out annually on approximately 0.5 million hectares. Due to the labour-intensive and costly nature of field inspections, official harvesting quality assessments produced by the Finnish Forest Centre are conducted on less than 1% of this area. For many years, the aspect with the greatest need for improvement has been thinning intensity. Harvester operators also require real-time information and feedback systems, because feedback on thinning quality is given in many cases after weeks or even months after the operation. It is assumed that harvesting quality can be improved through tree-level operator guidance, while at the same time enabling the collection of large amounts of forest-related data.

This study evaluates the feasibility of conducting follow-up harvesting quality assessments using only digital data sources: StanForD 2010-based harvested production (hpr) messages and stand-level tree maps derived from Ponsse Thinning Density Assistant (TDA) point clouds combined with external forest information databases (Metsakanta.fi service and Metsaan.fi data provided by the Finnish Forest Centre). A new methodology is introduced to automatically assess harvesting quality indicators, including residual stand structure, thinning intensity, and strip road geometry along machine trails.

The objective is to determine whether harvesting quality can be digitalised and assessed at scale without field measurements, enabling coverage of all harvested stands instead of small inspection samples. Additionally, the study examines whether the use of TDA-based data collection supports improved harvesting quality through operator guidance and feedback. By linking quality assessment with machine-generated data streams, the proposed framework represents a step towards scalable, transparent, and adaptive monitoring of forest harvesting operations.

Keywords: Thinning; MLS; Intensity; StanForD2010

Integrated Vision and Crane Control for Autonomous Log Handling

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Forestry operations are facing increasing structural challenges, including a shrinking skilled workforce, heightened safety requirements, and rising expectations for productivity with reduced environmental impact. These create a clear need for automation technologies that can support or eventually perform demanding tasks autonomously. In 2021, our AORO platform marked a significant milestone as the first fully autonomous unmanned forestry machine demonstrated live. While AORO successfully achieved autonomous navigation and partial crane automation in a forwarding task, it lacked the capability to autonomously complete the full log handling cycle. In particular, the crane could not operate all degrees-of-freedom autonomously due to the absence of grapple sensing and a dedicated vision system, restricting the system's ability to execute a complete log handling cycle that required complex motions of the grapple.

This work presents a new add-on system that closes this gap and enables full control over all crane's degrees-of-freedom. The solution extends the AORO machine with an integrated system that combines log detection, precise crane control, and coordinated motion planning. Together, these components allow the machine to perform a complete work cycle: navigate to a work area, identify scattered logs, grasp them securely, and pile them in an organized manner along the roadside.

To perceive the work environment, a dedicated stereo camera is mounted on the crane, providing a clear view of the logs within the operating range. A Convolutional Neural Network (CNN)-based detection model was trained to recognize and localize individual logs under realistic field conditions, including variable lighting and cluttered backgrounds. Once detected, the position of each log is estimated relative to the crane base using calibrated geometric transformations. This ensures that the crane can directly act on the detected targets without additional adjustment.

To achieve reliable and precise handling, the crane control system has been upgraded to operate all joints simultaneously. The grapple has been equipped with new sensors to provide direct feedback: a wired encoder measures rotation, and a wireless sensing solution monitors claw position. These additions significantly improve grasp accuracy and allow the crane to coordinate its movements more effectively during both pickup and placement.

A new motion planning approach based on S-curve velocity profiles coordinates all crane joints throughout each movement. This ensures smooth acceleration and deceleration, reducing abrupt motions that can destabilize logs or impose unnecessary stress on the machine. The result is controlled, efficient motion both when approaching a log and when transporting it to the piling location, contributing to stable handling and reduced mechanical wear.

The integrated system was validated in a public demonstration in which the unmanned machine autonomously navigated along a forest road, detected randomly scattered logs, grasped them, and piled them to one side of the road. The full cycle, from perception to final placement, was executed without human intervention. The demonstration confirmed robustness under realistic field conditions and provided tangible proof of system effectiveness, closing a critical gap in AORO's manipulation autonomy.

Keywords: smart-crane-control; computer-vision; machine-automation; forestry-robotics

Animal logging in an industrial economy: reasons for survival and future perspectives

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Pack-mules are the archaic logging system that prevailed in the Apennine mountains until few decades ago. Today, despite the dramatic reduction in the number of teams, this system still survives, contrary to all expectations. Given that the system has its merits and cultural value, there is an interest in preserving and enhancing it, perhaps even expanding it.

To do so, however, we must first determine the conditions that have allowed this archaic system to survive to this day, the unique assets that can be leveraged to maintain it, and the hurdles that must be removed in order to support a possible expansion – before all know-how is forgotten and the purportedly-selected breeds degenerate and die.

In order to achieve this goal, CNR teamed up with the main draught animals' associations active in Italy and developed a network of contacts with mule loggers – active, retired and newly equipped (yes, there are a few rare examples).

The research was based on face-to-face interviews and defined the characteristics of those businesses, the motivations of their entrepreneurs, the possibilities and methods for the preservation and eventual revival of mule logging in Italy.

Focus points were: the integration of animal and mechanized logging; the reduction of physical effort; the importance of animal selection and training; the capacity of achieving a minimum use intensity.

Keywords: Mule1; Logging2; Challenge3; Mountain4;

Barriers and Prospects for Biodegradable Hydraulic Oils in Forest Machines – Insights from Finland

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In Finland, the forest industry has taken several steps toward more sustainable wood procurement. For example, biogas-powered timber trucks have been introduced, and large companies now require that biodegradable chain oil is used in harvester heads. Biodegradable hydraulic oils entered Finland's market in the late 1980s and were adopted in forest machinery largely due to industry demand. However, serious malfunctions and mechanical failures were reported, and the requirement to use them was gradually withdrawn in the late 1990s and early 2000s. In Sweden, by contrast, biodegradable hydraulic oils are compulsory in forest machines, guided by a national standard (Svensk Standard SS 155434).

This study examined perceptions, experiences, and future prospects of biodegradable hydraulic oils in Finnish forest machinery. The research combined a nationwide survey of logging contractors with semi-structured interviews of forest machine manufacturers and an importer of biodegradable hydraulic oils. The aim was to assess whether biodegradable hydraulic oils are perceived as a threat or an opportunity in Finland and how historical experiences influence current attitudes.

An electronic survey was distributed in February–March 2025 to more than 900 forest machine members of the Trade Association of Finnish Forestry and Earth Moving Contractors (Koneyrittäjät ry), yielding 121 responses. In addition, interviews were conducted with representatives of Ponsse Plc, John Deere Forestry Oy, Komatsu Forest Oy, and Ajotek Oy.

The results indicate a lack of trust among logging contractors. Of the respondents, 61% considered biodegradable hydraulic oils more as a threat than an opportunity, while 27% viewed them positively. Forty percent had personal experience using such oils, and 83% reported observing or hearing about technical problems. The most frequently mentioned issues were failures of hydraulic pumps and motors, hose breakages, accelerated component wear, and poor cold-weather performance. Only 5% reported clear advantages, such as longer oil change intervals and broader operating temperature ranges.

Cost and reliability were key concerns. Biodegradable hydraulic oils were perceived as substantially more expensive than mineral oils, and their performance was often considered inferior. Nearly half of the respondents stated they could not imagine using them in the future unless reliability improved, prices became competitive, and performance matched that of mineral oils.

Manufacturers and the importer emphasized both risks and opportunities. Biodegradable oils can reduce the environmental impacts of hydraulic leaks and improve the sector's public image, but successful adoption requires careful product selection, adherence to recommendations, and investments in maintenance infrastructure. Negative experiences with early vegetable-based oils in the 1990s continue to shape attitudes and contribute to persistent distrust.

The findings suggest that biodegradable hydraulic oils represent both a threat and an opportunity, depending on stakeholder perspective. Wider adoption in Finland will require independent research, testing under local climatic conditions, harmonized standards, and clear economic incentives. Rebuilding trust is essential for enabling environmentally sustainable technological transitions in forest operations.

Keywords: Contractor; Harvesting; Sustainability; MineralOil

Towards a low-carbon wood supply chain: Improving logistics in the Polish context

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Efficient wood logistics is essential for minimizing operational costs and reducing greenhouse gas (GHG) emissions. In Poland, several symptoms of inefficiency—including the fragmentation of forest operations leading to frequent machine relocations, extended transport distances, and the need to move machines to designated parking locations after each working shift—highlight the need for a systematic and comprehensive assessment. To date, existing studies have predominantly focused on individual supply chain segments or specific stakeholder perspectives. A holistic assessment of the wood supply chain efficiency in Poland remains limited.

This study assesses the efficiency of the wood supply chain in two Regional Directorates of the State Forests distinguished by contrasting spatial forest structures. The first one is characterised by concentrated forest stands covering 294 thousand hectares, with 56 thousand cutting treatments per year resulting in 1.2 million m³ of harvested wood supplying 170 customers. The second is characterised by fragmented stands covering 188 thousand hectares, with 30 thousand cutting treatments annually resulting in 746 thousand m³ harvested supplying 181 customers. The analysis encompasses the entire process, from harvest planning to delivery to the processing plants, including harvesting, extraction, storage, assortment allocation to mills, and transportation. The study is based on historical data from 2019–2023, including the spatial distribution of forest compartments, harvested volumes by assortment, silvicultural treatments, the road network, and the demand for assortments from wood processing plants located throughout the country.

The business-as-usual (BAU) scenario derived from historical data was compared with three levels of improvement scenarios using a simulation–optimization approach implemented in ArcGIS Pro 3.4.0. The scenarios are structured hierarchically according to their decision-making impact: Level A addresses strategic logistics, Level B focuses on tactical infrastructure, and Level C deals with operational routines. Level A (three variants) examines alternative allocations of loading points to processing plants to minimize transport distances and applies harvesting concentration strategies to reduce machine relocations. Level B (two variants) evaluates different configurations and densities of loading points (storage sites). Level C (two variants) analyzes alternative machine destinations after the end of the working shift.

In total, twelve scenarios, including the BAU scenario, were developed and evaluated in terms of total operational costs, incorporating GHG emission costs per m³ of harvested, extracted, and transported timber across all feasible equipment combinations under Polish conditions. The results of this study will be presented and discussed, with particular emphasis on the performance of the analysed scenarios and the challenges associated with implementing the most cost-effective solutions.

Keywords: "logistics; efficiency; resilience; sustainability"

Automated Forest Stand Segmentation Using Airborne 3D Data and Machine Learning

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Reliable forest stand delineation is a fundamental prerequisite for forest management, harvesting system allocation, and spatial planning. Conventional stand boundaries are typically derived from visual interpretation in the field or from aerial imagery, making them time-consuming, experience-dependent, and only partially reproducible. In response to increasing disturbance dynamics and the demand for consistent spatial planning units, this study develops and evaluates a reproducible, data-driven approach for automated stand classification and segmentation based on airborne 3D data.

The methodological framework integrates airborne laser scanning (ALS), UAV-based laser scanning (ULS), and image matching from aerial imagery as alternative data sources. The workflow was tested in two independent Austrian study areas where all three airborne systems were acquired within a narrow temporal window: a 130-hectare forest management unit in Styria and a larger test area exceeding 1.000 hectares in Tyrol. Structural and site-related predictors were aggregated on hexagonal grid cells (314 m²) derived from point clouds and digital terrain models. These included vegetation height quantiles, mean and median canopy height, height variability, elevation, slope, aspect, and distances to forest roads and watercourses.

Forest development stages were classified using gradient boosting models trained on independent inventory data. Model performance was assessed via k-fold cross-validation. In the Styrian test area, strict class agreement reached 56.3% (Cohen's kappa = 0.49). Allowing a deviation of one adjacent development stage to account for structural transition zones increased overall accuracy to 82.3%. Moreover, the automated classification resulted in a 22.7% increase in within-class structural homogeneity compared to conventional stand delineation by forest experts, measured as a reduction in intra-class variance of canopy height metrics. Important predictors were the 75th percentile of vegetation height, median vegetation height, and elevation-related variables.

Pixel-level predictions were subsequently aggregated into operationally usable compartments using spatially constrained hierarchical clustering and graph-based region-growing algorithms. Small and isolated patches were reassigned to neighboring units, resulting in coherent and practically manageable stand polygons. The standardized workflow enabled direct comparison of data-source effects. ALS ensured homogeneous coverage over large areas, ULS provided higher structural detail at stand scale, and image matching represented a cost-efficient alternative but showed limitations in canopy penetration and terrain representation, influencing predictor stability and class separability.

The resulting digital stand maps provide a standardized spatial reference for deriving forest metrics such as growing stock, stem density, and diameter distributions. These compartments support harvest planning and facilitate rapid map updates following disturbance events. Overall, the integration of airborne 3D sensing and machine-learning-based segmentation provides a quantitative and scalable foundation for data-driven forest management and operational planning.

Keywords: ``LaDiWaldi"; ``Remote-sensing"; ``Machine-learning"; ``forest-inventory"

Multi-Modal Perception and Navigation Framework for Automated Driving of Forestry Machines

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Forest environments pose significant challenges for automated driving due to dense vegetation, irregular terrain, varying illumination conditions, narrow skid roads, and limited or unreliable GNSS availability. In contrast to structured road environments, skid roads often lack clear boundaries and may contain unpredictable obstacles such as branches, uneven ground, and irregularly spaced trees. Reliable automated driving in such environments therefore requires robust perception, mapping, and navigation components that remain stable under highly unstructured and dynamically changing conditions.

To address these challenges, a multi-modal perception and navigation framework has been developed and deployed on a full-scale forestry machine. The framework integrates deep learning-based visual perception with LiDAR-based mapping and localization and extends the navigation pipeline with occupancy-aware path planning.

For semantic perception, a state-of-the-art YOLO26 model is trained using a combination of newly annotated forestry datasets and previously collected data. The dataset includes skid roads, tree trunks, and typical environmental structures encountered during timber extraction. The trained model is deployed directly on the forestry machine and enables real-time detection while driving along skid roads. This visual module provides semantic understanding of the driving corridor and surrounding objects, supporting corridor recognition and obstacle awareness under varying lighting conditions and partial occlusions, thereby establishing a foundation for vision-supported driving automation functions in forestry applications.

In parallel, a LiDAR-based landmark extraction method was implemented for geometric mapping and localization. Trees with distinct cylindrical trunk characteristics are detected in real time and parameterized as geometric primitives. These tree landmarks are incorporated into a SLAM framework to build a consistent map and estimate vehicle pose during operation. While this landmark-based approach provides accurate localization when trunk geometry is clearly observable, performance can degrade in scenarios where trunk features are irregular, partially occluded, or less distinguishable.

To improve robustness, an occupancy grid mapping module was introduced as a complementary environmental representation. Rather than relying exclusively on explicit trunk landmarks, the occupancy grid captures the spatial distribution of nearby objects along skid roads and provides a denser representation of occupied space. This representation compensates for situations in which landmark detection becomes unreliable and offers improved environmental awareness in complex forest conditions.

Building upon the perception and mapping modules, a multi-modal path planner, referred to as FlowPlanner, is developed. The planner integrates information from tree landmarks, tree clusters, and reference paths to generate a combined guidance flow field. Based on this flow representation, multiple candidate trajectories are generated online and evaluated with respect to alignment, safety margins, and kinematic feasibility. The most suitable candidate is selected as the local goal path. This approach enables real-time generation of feasible driving trajectories and supports exploratory navigation in partially unknown forest environments.

Initial field experiments in real forest conditions indicate the functional feasibility of the proposed framework. The modular system architecture supports incremental refinement and integration of additional perception and planning components, providing a scalable foundation for progressive automation in demanding forestry operations.

Keywords: Automation; Perception; SLAM; Navigation

Two-stage trucking in NZ steep-land harvesting.

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Two-stage trucking systems are increasingly used in steep-land harvesting in Aotearoa New Zealand to reduce the need for the quality of roading and landings required to allow access for on-highway high productivity motor vehicles (HPMV's). In these systems, stems or processed logs are trans-shipped between a constrained extraction/processing landing and a larger storage and load-out skid using a dedicated intermediate truck. This study synthesises elemental time study findings from nine two-stage systems based on eight different intermediate truck configurations, spanning two widely used platform types: (1) modified 6WD articulated dump trucks, and (2) off-highway/on-highway log trucks (6x8 and 8x8). Data were collected across multiple harvesting contexts (ground-based and cable), with cycle elements separated into loading, travel loaded, unloading, travel unloaded, and delays. Intermediate road distance and grade were measured in segments, and payloads were estimated using truck scales or log-count/volume methods.

Across case studies, haul distances ranged from 350 m to 5,440 m, with average loaded speeds typically between 2 and 7 m/s depending on road profile and surface condition. Productivities ranged from 19 to 44 tonnes per productive machine hour (t/PMH), with utilisation 73–96%. Results indicate that intermediate-truck productivity is primarily determined by (i) haul distance and road profile, (ii) effective payload capacity (including the ability to use a trailer and the degree of load sorting), and (iii) loading/unloading system design—particularly access to loaders and interference with other landing/skid activities. Where long haul distances combined with constrained payload (e.g., inability to use a trailer), travel time became dominant and reduced throughput, sometimes requiring additional truck hours to avoid bottlenecking the prime mover. Conversely, higher payload capacity and/or shorter leads could offset challenging grades, and well-integrated landing/skid layouts reduced interference delays.

These findings support a practical design implication for harvest planners: intermediate trucking should be treated as a system component whose performance is jointly shaped by truck configuration, road geometry, loader availability, and landing/skid layout, rather than by truck platform alone. When these elements are aligned, two-stage trucking can provide access to steep or erosion-prone settings while potentially maintaining or improving overall harvesting productivity and reducing safety and environmental risk.

Keywords: two-stage; trucks; productivity; steep-lands

The role of replacing pure stands with mixed stands in improving forest productivity, resilience, and product diversity

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Mixed species forests have been increasingly recognized as an important pillar of sustainability driven ecosystem management under uncertain and more frequent extreme environmental and social conditions. Although knowledge about the resilience of mixed stands has remained somewhat fragmented, the growing frequency of climate related risks has indicated that the importance of mixed stands is increasing and that the long term resilience of mixed forests is generally higher than that of pure stands. This review synthesized available scientific research on the diversity of benefits when replacing pure stands with mixed forest stands, especially focusing on stand productivity, resilience, and product diversity in mixed stands compared with pure stands, integrating findings from different forest ecosystems. The review concluded that mixed stands generally achieved higher stand level productivity through more diverse and complementary resource use, sometimes resulting in increased growth efficiency. Furthermore, the review found that mixed stands expanded the range of available forest products, improving timber assortment diversity, supporting higher biodiversity (including fauna), and increasing the diversity of non timber products such as fruits and other edible, medicinal, and bio based materials. By combining international research with regionally relevant insights, the review added value for forest management, where the improved resilience associated with species mixing has been acknowledged but insufficiently examined in relation to forest value chains and long term ecological and economic stability. The synthesis also contextualized the important role of replacing pure stands with mixed stands for strengthening forest ecosystem services, enduring climate related stressors, and supporting a more diversified and resilient forest based silviculture.

Keywords: Silviculture; Diversified forest management

From Critical Bottlenecks to Resilient Breakthroughs: Innovative Insights from Timber Trucking Entrepreneurs Across Europe

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Wood supply chain and transportation logistics are critical drivers of resilient forest value chains, enabling the reliable, sustainable, and cost-effective flow of a unique renewable resource. In recent years, operational volatility has increased due to disturbance-driven salvage wood peaks, tighter labor markets, and rising expectations about emissions. Despite the sector's relevance to resilience-oriented innovation, empirical findings on timber trucking remain fragmented and limited to single-country settings, thereby constraining the availability of transferable evidence for research, management, and policy.

We present insights from a representative empirical survey of more than 300 wood transportation enterprises across eight European countries. Our study was designed for meaningful cross-country comparison while respecting national institutional and operational contexts in Austria, the Czech Republic, Finland, Germany, Italy, Latvia, Poland, and Portugal. The selected countries reflect Europe's diversity in forest ownership structures, workforce conditions, climatic zones, disturbance histories, transport infrastructures, and modal splits. Our overarching objective is to provide a robust empirical baseline on constraints, practices, and transition priorities in timber transportation logistics, with an explicit focus on resilience-relevant leverage points.

Our survey development followed a structured co-design process. First, we established a shared conceptual approach linking transportation logistics to resilience and sustainability. This framework included contingency planning, coordination interfaces, regulatory conditions, workforce constraints, and digitalization. Second, we drafted a standardized questionnaire with more than 60 questions. We refined it through multiple rounds of feedback from national experts and stakeholders. Third, we piloted the instrument to ensure measurement equivalence across countries, translated it into national languages, and deployed it as a harmonized online survey.

Across Europe, entrepreneurs report a strong convergence in perceived bottlenecks. Timber trucking resilience is widely constrained by economic pressure, persistent labor shortages, and an aging driver workforce. Infrastructure limitations, especially at the interface between forest roads, terminals, and stockyards, are frequent. Preparedness for disturbance-driven peak volumes is often perceived as insufficient. Disruption risks are well recognized, yet contingency planning and coordinated crisis routines across value chain actors remain underdeveloped. Respondents identify actionable transition pathways. Stronger vertical coordination between forest owners, harvesting, carriers, and industry, together with horizontal collaboration among transport actors, is seen as essential to stabilize flows and improve utilization. Multimodal and multi-echelon unimodal transport are viewed as strategic

options where terminal access and service quality are adequate. These approaches offer additional capacity for longer distances and peak periods, and support emissions reduction.

Building on these insights, interconnected leverage points emerge. These include faster digitalization and data-driven planning; workforce development, training, and retention; crisis-ready governance with clear routines and pragmatic regulatory flexibility during disturbances; investment in infrastructure and buffering capacity enabling operational flexibility and multimodal integration; and targeted investment support for modernization, green technologies, and collaborative innovation partnerships. Together, these pillars can translate recurring bottlenecks into resilience-oriented breakthroughs in European timber transport logistics.

Keywords: Forest-Value-Chain-Resilience; Timber-Transport-Logistics; Leverage-Points; Cross-National-Survey

Automated Detection of Bark Stripping from LiDAR Data Using Convolutional Neural Networks

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Bark stripping is a major disturbance factor in Central European forests and leads to reduced growth, increased susceptibility to fungal infection, and elevated mortality risk. In operational forest management, severely damaged trees often need to be removed in order to avoid economic losses and secondary infections. Reliable and objective detection of bark stripping is therefore highly relevant for precision forestry and technology supported harvesting decisions. This study investigates whether bark stripping can be detected automatically using Light Detection and Ranging (LiDAR) data and Convolutional Neural Networks (CNN) and evaluates the potential integration of such an approach into LiDAR based forest inventory workflows.

Data acquisition was carried out in Styria in Austria on 37 sample plots with and without visible bark stripping. In total, 71 trees with bark damage were recorded across these plots, containing 172 individual bark stripping wounds. Three laser scanning systems were used, including a terrestrial laser scanner (TLS) Riegl VZ600i, a mobile laser scanner XGrid Lixel L2 Pro (MLS), and a consumer grade device Apple iPad Pro. The TLS point clouds provided intensity, reflectance, amplitude, and RGB attributes for each measured point, whereas the MLS point clouds delivered RGB and intensity attributes, and the tablet based system RGB attributes only.

Tree stems were unwrapped from the point clouds to generate two dimensional stem representations. Bark wounds were manually delineated and served as reference data. From these labeled stem surfaces, 100 × 100 pixel image patches with a spatial resolution of 2.5 mm per pixel were extracted to generate training and validation datasets. Initial model development focused exclusively on TLS data, as this dataset provided the most complete geometric and radiometric information. A pre trained ResNet 18 architecture was fine tuned for binary classification of damaged versus undamaged stem patches.

First experiments using grayscale patches derived from TLS point clouds achieved an overall classification accuracy of 76 percent on the independent test dataset. Precision exceeded recall, indicating a conservative model behavior with a tendency to classify uncertain patches as undamaged. The resulting F1 score reflected this imbalance between omission and commission errors. Ongoing work investigates multi channel input configurations combining RGB and LiDAR derived features as well as larger spatial contexts in order to increase detection sensitivity.

The presented workflow demonstrates the feasibility of automated bark stripping detection from LiDAR data and provides a foundation for integrating damage detection into digital forest inventory and decision support systems. Such an approach can support automated timber harvesting in identifying trees that require priority removal and contributes to the advancement of precision technology and remote sensing in forest operations.

Keywords: LaDiWaldi; LiDAR; Inventory; CNN

Satellite-Based Low-Latency Teleoperation of Forestry Delimbers for Remote Full-Tree Operations

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Our project focuses on the development of a teleoperation system for a forestry delimber operating in full-tree applications in Canada. In many regions, full-tree processing involves repetitive tasks: feeding stems, delimbing, cutting to prescribed lengths, handling, and stacking. These operations require precision, are physically demanding, and take place in remote environments. The forestry sector faces a persistent shortage of skilled operators, limiting production capacity and increasing pressure on crews. Operational costs are significant, particularly due to long distances between cities and harvesting sites, often exceeding 120 km. Transporting operators to remote sites adds logistical complexity and expense.

A major constraint is the lack of reliable cellular connectivity. Harvesting sites are commonly located outside LTE or 5G coverage in Canada, preventing the use of conventional teleoperation solutions that depend on terrestrial infrastructure. This connectivity gap, combined with labor shortages and high costs, motivates the need for an alternative approach.

To address these challenges, we are developing a satellite-based teleoperation system for forestry delimbers. The objective is to enable a remote operator to control a machine in real time from an operations center near a mill or service hub. By centralizing operators in a controlled environment, this approach reduces travel time, improves working conditions, optimizes workforce allocation, and enhances operational efficiency. It also extends opportunities for experienced operators who may no longer wish to work full-time in remote forest conditions.

A key technical challenge lies in communications performance. Teleoperating a forestry machine requires continuous transmission of video streams and sensor data, including onboard cameras and lidars used for environmental perception and positioning assistance. Satellite networks introduce constraints in bandwidth and latency. To ensure feasibility, we developed advanced data compression and stream optimization mechanisms. The system architecture maintains low end-to-end latency to preserve precise and safe machine control while minimizing bandwidth usage. Our operational target is to keep total data consumption below 4 terabytes per month, including video and command streams required for teleoperation.

The platform incorporates adaptive bitrate strategies that adjust stream quality according to network conditions. Safety mechanisms guarantee predictable machine behavior in the event of communication degradation or temporary link interruption. Edge processing capabilities are integrated on the machine to prioritize critical control data over auxiliary sensor streams, ensuring stable command responsiveness under fluctuating satellite link conditions.

An initial validation phase is conducted using a Caterpillar delimber equipped with our teleoperation system on a controlled private site. These trials evaluated sensor integration, satellite communication robustness, control stability, and overall system performance under realistic conditions. Quantitative metrics collected during testing included end-to-end latency, packet loss resilience, and bandwidth utilization.

The next phase includes operational trials in an active forest environment scheduled for summer 2026, assessing performance under real production constraints and varying weather conditions.

This project demonstrates that reliable, safe, and economically viable satellite-based teleoperation of forestry delimiters is achievable in remote environments, supporting a structural evolution in heavy forestry machinery operations.

Keywords: Teleoperation; Delimiter; Low-latency

Rut depth and Stand damage analysis after Winch-Assist harvesting

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Winch-assisted harvesting technology is becoming increasingly common in Alpine countries and in forests on steep terrain. However, research into the impact of this technological system on forest soil and stands remains limited. In a study conducted at three different sites, we measured several parameters on sample profiles perpendicular to the skid trail, including rut depth and compaction, skid trail slope and width, number of machine passes, coverage of the trail with logging residues, residue thickness, and soil water content. The average rut depth of skid trails across all sites was 14.9 cm, with the average depth in Žetale at 23.1 cm, in Log at 14.9 cm, and on Pohorje at 13.1 cm. We found that rut depth increases statistically significantly with the number of machine passes, and that higher soil water content generally increases rut depth, although the effect is small. The slope of the skid trail has a significant effect in Žetale and Pohorje, as terrain slope increases, rut depth increases only in Pohorje, while it decreases at the other two sites. We also analysed stand damage on circular sample plots of 100 m², distributed systematically across the site. The proportion of damaged trees was highest in Pohorje (52.5%), followed by Log (51.7%), and lowest in Žetale (38.6%). The average size of damage was highest in Pohorje (230.2 cm²), 178.9 cm² in Žetale, and lowest in Log (172.3 cm²). Most damage occurred on the stems, with the least in the crowns of standing trees. We found that tree species and diameter at breast height significantly influence the occurrence of tree damage. Compared to non-assisted mechanised harvesting, winch-assist technology is reported to cause less damage to forest floors due to the use of a winch and smaller wheel ruts, although this depends on several factors. The results of our study, compared to others that also examined winch-assist harvesting, show that average wheel rut depths are greater in most cases. A comparison of studies on stand damage during mechanised harvesting without winch assistance with our results showed, that the proportion of damaged trees was higher, while the average size of damage was lower at our sites than in some other studies. As has been established, soil and stand damage is influenced by many different factors, so further studies at different research sites are needed to obtain a better assessment of the suitability of winch-assisted harvesting technology for specific working conditions.

Keywords: Winch-assist-harvesting; rut-damages; stand-damages; steep-slopes

Comparative life cycle assessment of hybrid and conventional diesel harvesters

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Growing environmental concerns and increasing pressure on natural resources have intensified the demand for robust sustainability assessment tools in industrial sectors. Life Cycle Assessment (LCA) enables the systematic quantification of material and energy inputs, as well as associated environmental emissions, across the entire life cycle of products and technologies. In mechanized forest operations, LCA provides a comprehensive framework for evaluating the environmental implications of emerging solutions and informing the transition toward lower-emission technologies, such as hybrid harvesting systems.

This study evaluates the environmental performance of hybrid harvester engines compared to conventional diesel-powered harvester engines using a cradle-to-grave approach. The system boundary includes component manufacturing, machine assembly, operational use over the engine lifetime, maintenance, and end-of-life treatment. The functional unit is defined as one engine over its operational lifetime. The LCA model was developed in SimaPro using the Ecoinvent database and IPCC characterization factors. Environmental impact categories considered include global warming potential (GWP), acidification, eutrophication, human toxicity, and resource depletion.

Field measurements from operational trials in Eastern Canada indicate that hybrid harvesters consume approximately 20% less diesel fuel under comparable stand and working conditions as compared to diesel harvesters. Preliminary results for the conventional diesel engine show that the use phase dominates total life cycle impacts, contributing most emissions across impact categories. Although hybrid engines require additional components such as electric motor and power pack units, preliminary scenario modeling suggests that operational fuel savings offset these additional embodied impacts over the engine's lifetime. These early findings indicate that hybrid harvesting technology has strong potential to reduce the environmental footprint of mechanized forest operations, particularly where full electrification remains constrained.

Keywords: LCA; Harvester; Hybrid; Emissions

Analyzing resilience in electric truck charging stations in forestry transport

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To meet climate goals and limit global warming there is an urgent need to decarbonize road freight transport, including the forestry sector's transport. Previous studies have shown that electrification is an effective means for carbon abatement in freight transport and will play a key role. In the project TREE (Transition to efficient electrified forestry transport) 12 electric timber and wood chip trucks are operated in commercial operation at seven different sites in Sweden, illustrating the feasibility to electrify forestry sector's transports. The TREE project has pronounced that access to reliable charging is critical for efficient electrification. A single charger failure, due to technical malfunction, limited power supply, or waiting times at the charging point, can render an entire route infeasible or that an entire region is not accessible. This creates a form of systemic fragility, where the operational viability of electric trucks is highly sensitive to disruptions at individual charging points. Such vulnerabilities reduce system reliability, increase operational risk, and may slow down the adoption of electric trucks. In this study, we aim to analyze and improve the robustness of charging infrastructure for heavy electric trucks in forestry transport. We propose indicators for assessing the robustness of a charging network. To assess the robustness of a charging network, we combine a fleet planning tool for mixed fleets of electric and diesel trucks with Exploratory Modeling and Analysis (EMA) to run many simulations with different potential charging failures implemented and different combinations of trucks. Based on the results, we explore the robustness of a charging network in a region. The aim is to use the results to propose improvements in the charging network.

Keywords: electrification; resilience; charging; modeling

Transforming Steep-Terrain Forestry: Specialized Winch-Assisted Platforms and Integrated Excavator-Based Earthwork and Harvesting Solutions

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Steep-terrain forestry (>30°) demands a radical departure from conventional machinery to balance operational efficiency with soil protection. This study evaluates a dual-solution framework developed by MSE: the "Shin-Raptor II," a specialized 6,400 kg class lightweight winch-assisted (WA) base carrier, and the "Feller Buncher Saurus (FBZ)," an innovative attachment for integrated earthworks and harvesting. The Shin-Raptor II is a specialized platform that redefines steep-slope felling by eliminating the conventional crane arm. Its compact 6,400 kg design, combined with a unique chassis-integrated felling architecture, maintains an exceptionally low center of gravity and minimizes soil impact. Powered by a fully synchronized Winch Assist (WA) system, this lightweight machine achieves superior vertical mobility and high-traction performance on 45° slopes where traditional heavy harvesters fail. Its 10° engine-oscillation mechanism further ensures operational reliability under extreme tilt. Complementing this specialized carrier is the FBZ, designed to transform standard 0.45 m³ class hydraulic excavators into multifunctional infrastructure units. The FBZ uniquely integrates a 0.45 m³ excavation bucket with an eccentric pull-cut blade, enabling a single machine to perform slope profiling, stump removal, and road construction while simultaneously executing high-speed felling. This integrated workflow significantly reduces machine traffic and operational costs by eliminating the need for separate road-building equipment. Furthermore, its "pull-cut" geometry allows for the efficient processing of high-density broad-leaved timber. Together, these technologies provide a scalable framework for precision forestry, balancing extreme mobility with comprehensive operational versatility.

Keywords: Steep-terrain; Winch-assisted; Chassis-integrated; Road-harvesting

Managing uncertainty in wood supply – a Monte Carlo approach to risk analysis

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Forest operations managers handle multiple sources of uncertainty when planning wood supply. Wood sourcing for Nordic forest industries typically include both internal and external suppliers, where the first-line for solving operational deviations from delivery plans involves re-planning of internal supply operations.

This paper presents an adaptation of the typical monthly wood supply plan in order to quantify the risk of varying supplier portfolios.

The approach is used in masters-level instruction in industrial wood supply. The student exercise is done in 3 steps over 2 teaching days. The first step consists of selecting a supply structure aimed to secure year-round supply to a generic pulp mill. The mill supply structure is defined by students' selection of annual wood orders from 5 supplier categories (2 internal and 3 external). An initial tactical plan is drafted for monthly deliveries per supplier category to maintain monthly stock intervals. At this stage the planning is purely deterministic, and can be assisted by an initial optimization, including consideration to seasonal trends for wood availability. The second step is then to test the draft plan using Monte Carlo simulation with supplier-specific distributions of monthly demand fulfillment. The resulting frequency of stock levels exceeding defined goal intervals is then used to adjust the annual order from the respective supplier categories. After adjustment, the third step is to explore internal responses to reduce the risk for exceeding the goal stock intervals. The response options include i) time horizon for response and ii) strength of response.

The distributions of monthly demand fulfillment (%) for the respective supplier categories are described with a 2-parameter gamma-distribution. The estimation of the gamma parameters is based on 2 years of pulpwood deliveries to Swedish SCA from 25+ external supply organizations and 6 internal supply regions. Multivariate clustering was used to segment the suppliers into six main categories, including spot contracts. The respective distributions were estimated in relation to two base-lines: i) originally contracted monthly volumes and ii) revised monthly contract volumes.

The approach enables adaptation of a typical monthly master plan to simulate various supply system risks. The approach serves well as a practical introduction to understanding uncertainty and risk in wood supply.

Keywords: uncertainty; risk; tactical planning

Session 4

Scaling Drought-Induced Scots Pine Mortality for Operational Risk Assessment in Forest Value Chains

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Climate-driven forest mortality is having an increasingly significant impact on harvesting intensity, the stability of wood flows, and the medium-term availability of timber. However, translating climate signals into operationally meaningful indicators remains challenging, as the strength of the relationship between drought and mortality depends on the spatial scale. This study evaluates the extent to which climatic water balance (CWB) can explain Scots pine (*Pinus sylvestris* L.) mortality at different levels of forest management in Poland: forest district (operational scale) and regional directorate (strategic scale).

Mixed-effects modelling was employed to distinguish ecological drivers from scale-dependent variability, employing long-term mortality records and high-resolution climate data. The model's predictions were expressed on a logarithmic scale of relative mortality. Drought-related mortality was found to range from approximately 6×10^3 to 2×10^5 m³ at the regional directorate level (mean standing volume: 61,755,798 m³), and from 2×10^1 to 7×10^2 m³ at the forest district level (mean standing volume: 224,213 m³).

The study shows that spatial aggregation strengthens the relationship between drought and mortality. Short-term harvest scheduling and resource allocation are complicated by the strong influence of local site conditions and stochastic disturbances on mortality variability at the forest district level. Local variability diminishes at broader spatial scales, allowing a coherent multi-year drought signal to emerge and impacting mid-term timber supply and processing capacity planning.

The results indicate that spatial scale is an essential component of climate risk assessment for forest operations. Identifying the appropriate level of aggregation enhances mortality forecasting, supports adaptive harvest planning, and makes forest-based value chains more resilient under increasing climate stress.

Keywords: operations, climat, scaling, mortality

Agentic AI as a Decision Support Tool for Resilient Small-Scale Forest Management

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Resilient forest value chains depend on the adaptive capacity of forest managers at all scales. Small-scale forest owners, who manage a substantial share of Europe's forest area, play a critical role in ensuring sustainable timber supply, safeguarding biodiversity, and maintaining multifunctional landscapes. However, their decision-making environment is becoming increasingly complex and uncertain. Climate change intensifies disturbance risks such as drought, storms, and pest outbreaks; timber markets are volatile and globally interconnected; and regulatory as well as societal expectations regarding ecosystem services, carbon sequestration, and habitat protection continue to grow. At the same time, many small-scale forest owners operate with limited access to specialized advisory services or advanced analytical tools. While innovation in harvesting technology, digital monitoring, and smart operations has advanced considerably, decision support solutions tailored specifically to the realities, constraints, and objectives of small-scale forestry remain underdeveloped.

A prototype AI-based decision support system designed to strengthen adaptive forest management at the holding level will be presented. The system builds on a systematic review of recent advances in generative and agentic artificial intelligence and translates these developments into a practical forestry context. Functioning as an interactive and context-aware assistant, the AI supports decision-making in complex and dynamic environments. By integrating stand-level data, owner-defined objectives, risk considerations, and regulatory constraints, the system generates context-sensitive management options aligned with multifunctional forest management and biodiversity goals. It structures trade-offs between economic performance, ecological resilience, and long-term sustainability, thereby enhancing transparency in strategic planning.

The study is showcasing how agentic AI can translate complex data, expert knowledge, and scenario assumptions into actionable guidance for decentralized forest managers. By empowering small-scale forest owners with adaptive, user-oriented digital tools, this approach contributes to strengthening resilience and sustainability across the whole forest value chain.

Keywords: "Agentic-AI; Innovation; Decisionmaking; Digitalization"

Impact of reduction in idling times on the GHG emissions of forest machinery: A scenario analysis using machine big data from Finland

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The idling of forest machines reduces the energy and cost efficiency of wood-harvesting operations. This study estimated the idling times of forest machines using automatically collected machine big data. The study also examined the impact of machinery type, harvesting enterprise, seasonal variation, engine power, and machine manufacturing year on fuel consumption during idling. Furthermore, a scenario approach was used to describe the influence of idling times on the volume and price of carbon dioxide (CO₂) emissions. The dataset included monthly data from 2021–2024, covering ten Finnish logging enterprises with a total of 28 harvesters and 23 forwarders.

The results showed that the proportion of idle time of harvesters and forwarders regarding the total operating hours was 14.0% and 11.1%, respectively. Significant differences were observed between harvesting enterprises, averaging from 6.7% to 18.2%. Idling proportions were also found to be around 14%-unit higher in winter months (November–February) than in summer months (May–August). Average fuel consumption during idling was 4.28 L h⁻¹ for harvesters and 3.38 L h⁻¹ for forwarders. Greater engine power was associated with increased fuel consumption when idling, and vice versa newer machines exhibited greater fuel consumption during idling.

Annual idle-related CO₂ emissions for wood-harvesting machinery in Finland were estimated at approximately 10,700 metric tonnes (t) with costs equivalent to €48 million. Reduction in idling by 25–50% could cut emissions by approximately 2,700–5,300 t CO₂ and generate additional revenue up to €55 million when the reduced idle engine hours were transferred into productive hours. If idling is reduced by 100% and all the reduced idling time was assumed to be productive working hours, CO₂ emissions from harvesters and forwarders would be 30,309 t CO₂ greater, whereas the annual revenue would exceed €120 million.

Based on the study, it can be concluded that understanding, as well as acknowledging, the influence of idling has a positive impact on energy and cost-efficiencies, while also ensuring more environmentally friendly wood-harvesting operations. The research strengthens the foundation for low-emission and efficient machine operations, but further studies on idling are still needed outside the forest sector as well. Therefore, we recommend that future research focus on assessing the impacts of idling in other machine segments both in Finland and globally, utilizing automatically collected machine data.

Keywords: CO₂-emissions; machine-data; idle; wood-harvesting

Evaluation of a system for forecasting volume and location of logging residues at stand level and pathways toward system automation

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Demand and price for logging residues in Sweden have increased due to the security situation in Europe and ambitions for energy independence and low-carbon energy systems. Accurate information on the volume and spatial distribution of logging residues from final fellings is therefore highly valuable for contractors, wood fuel suppliers and end-users (heating and combined heat-and-power plants). More than 15 years ago, Skogforsk developed a system for forecasting and positioning logging residue volumes at stand level using harvester production files. Implemented through the calculation module “hprCM”, the system is used by several forest companies. For accurate forecasts, it is essential that harvester operators correctly distinguish fuel-adapted areas from non-adapted areas in the stand. In practice, the harvester and forwarder often need to reinforce strip roads and wet areas with logging residues to prevent soil damage. These adjustments currently rely on manual input via keyboard or touchscreen in the onboard computer.

Within the Swedish Energy Agency-funded project “Improved forecasts of logging residues for precision planning”, we conducted a large-scale evaluation of the system by comparing forecast data with measurements from heating plants for several hundred wood chip deliveries. The evaluation revealed a large variation in how contractors used the system and in how well the forecasted volumes matched the measured volumes at the plant. This analysis formed the basis for developing improvements to the system.

One of our proposed solutions is to automate the registration process by using sensor technologies in modern harvesters. We carried out a field study in central Sweden, combining machine data with high-accuracy ground-truth measurements. Through this study, we identified key variables for automating the registration process. In the mid-term, if implemented, automated registration of logging residue volumes can reduce the cognitive load on operators, improve the reliability of forest fuel stock levels, and strengthen supply security.

Keywords: hpr-file; StanForD; planning; supply-chain

Management of Log Truck Weights in the US State of Georgia

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Log truck weights in the US state of Georgia are governed by state law, including limits for gross vehicle weight, single axle, and tandem axle weights. A very small percentage of loads are inspected by law enforcement, however. Some forest products mills have internal policies regarding the weight of delivered loads to reduce liability and protect mill infrastructure. The objectives of this study were to 1) evaluate the prevalence of mill weight policies, 2) document the structure of mill weight policies, and 3) analyze the variability in the weight of loads delivered to Georgia mills. We conducted a survey of Georgia mill-owning companies and obtained a sample of nearly 130,000 mill scale tickets from cooperating mills. Survey responses were received from owners of 27 Georgia mills representing 14.7 million tonnes of annual wood consumption (33% of annual wood consumption in the state). Eighty percent of companies had instituted an internal weight policy to control gross vehicle weight (GVW) of delivered loads. The stated reasons for instituting weight policies included liability reduction, improvements to highway safety, and protection of mill infrastructure. The weight policies were effective at preventing the delivery of grossly overweight loads (>5,400 kg over legal limit). Only 45% of delivered loads were within ± 1.5 tonne of the legal GVW limit and 27% of delivered loads were at least 1.5 tonnes below the legal limit. Improved management of truck payload by logging businesses could reduce hauling costs and improve timber transportation profitability in the state.

Keywords: Forest Logistics; Efficiency; Safety

Visual Estimation vs. TLS-Based Centre of Gravity: Quantifying Directional Misjudgement in Tree Felling

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Accurate estimation of a tree's expected leaning direction is essential for safe and controlled felling, particularly in complex crown architectures or winch-assisted motor-manual felling operations. In practice, such decisions rely primarily on visual assessment by experienced forestry workers. The extent to which this estimation reflects the tree's actual mechanical mass distribution and the direction of its centre of gravity (CoG) remains insufficiently quantified. This study compares personal visual tree assessments with terrestrial laser scanning (TLS)-derived CoG directions and extends the analysis to operational implications in winch-assisted motor-manual felling.

54 trees were independently assessed by three experienced workers (162 assessments in total). Each worker estimated the direction in which the tree was most likely to fall. For each tree, a three-dimensional CoG was calculated using TLS-based quantitative structure models (QSM). Monte Carlo simulations were applied to consider structural and density-related uncertainties. Across all assessments, the mean absolute deviation between personal visual assessments and TLS-derived CoG directions was 48° (median 35°), with extreme deviations reaching 141° (95th percentile). Differences between workers were small relative to the overall variability, indicating that uncertainty was not just limited to individual performance. Only 13% of assessments fell within ±10°, and less than half were within ±30°. This demonstrates limited precision at operationally relevant tolerances. Error patterns revealed systematic directional tendencies rather than random scatter. The forest workers frequently showed similar assessments of individual trees. Nevertheless, these assessments did not consistently align with the TLS-derived CoG directions, suggesting that visual assessment does not automatically imply mechanical accuracy. The observed deviations suggest that visually prominent features, such as stem curvature or inclination, strongly influence judgments, while less visible crown mass asymmetries that shift the CoG may be underestimated. Building on the three-dimensional CoG modelling, the study is being extended to quantify the mechanically required winch cable attachment height for each tree. This allows the geometric consequences of mass displacement to be assessed beyond directional estimation. These attachment heights will be compared with practitioner-based height selection in winch-assisted motor-manual felling, providing an operational perspective on CoG displacement.

Overall, the research indicates that personal visual tree assessment alone is insufficient to reliably capture the mechanical mass distribution of complex tree structures. The integration of laser-based CoG modelling with practitioner-based assessment establishes a framework for quantifying the boundaries of visual judgment, thereby promoting safety-oriented decision-making in forestry operations.

Keywords: QSM; Direction; Assessment; Felling

Real-Time Wheel Slip Estimation for Forestry Machines based on a combined Wheel-Encoder and RADAR Approach

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Heavy forestry machinery like harvesters or forwarders may damage machine operating trails during their operation by causing rut formation. This damage is mostly due to a combination of the loaded weight of these machines and soil condition, which can also result in increased wheel slip. Therefore, having a method to calculate slip in real time will result in a better understanding of caused soil damage.

The purpose of this presentation is to estimate wheel slip of forest machines in real time on machine operating trails by proposing a combined radar and wheel-encoder approach. The proposed solution is independent of machine make and model since it relies completely on external sensors making it modular for integration into existing systems. The core of this approach relies on using one wheel encoder on each side of each bogie axle to measure wheel rotation speed. A radar is then used to measure the real velocity of the ego vehicle, which is independent from wheel slip. As of current knowledge, there are no control systems on forest machines that use RADAR to calculate ego velocity. By evaluating both of these values, wheel slip can be numerically computed in real time. The evaluation of this method is currently being assessed in an ongoing project.

By providing real time slip calculation, advanced systems (like operator assistance or autonomous driving modes) can utilize it and indicate if operation of the machine can continue or if it should be halted, as predicted rut depth exceeds regulatory limits.

Keywords: Driving-Assistance; Sensors; Slippage; Terramechanics

Powering Forestry in Winter: Establishing a Battery Test Lab for Electrified Forestry Machinery

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Electrification is emerging as a key technological pathway for future forest harvesting systems to address existing challenges. These include reducing greenhouse gas emissions, improving energy efficiency, and strengthening the resilience of the forest sector to external disruptions, as it is currently heavily dependent on fossil fuels for harvesting and in-forest operations. Major manufacturers such as Komatsu Forest and Ponsse have recently introduced hybrid drivetrains in concept and prototype machines, paving the way also for a transition towards fully electric machines. However, battery-electric solutions in forestry face substantially different operational demands compared with on-road vehicles. Harvester and forwarder duty cycles are characterised by short, repetitive high-power peaks, complex crane operations and highly dynamic load profiles. At the same time, machines in northern regions routinely operate at temperatures down to $-25\text{ }^{\circ}\text{C}$ or colder. Such conditions strongly influence battery power output, usable capacity, charging behaviour and long-term degradation. While most battery research is conducted under standard laboratory conditions or according to automotive driving cycles, dedicated studies for forestry applications under cold-climate conditions are essentially non-existent. This represents a critical knowledge gap for harvesting system design, system selection and reliable winter operation planning and therefore a boundary for a future implementation of electric forestry machinery.

To address this gap, we are establishing a commercial-scale battery testing laboratory at the Swedish University of Agricultural Sciences (SLU), Department of Forest Bioeconomy and Technology in Umeå. The facility will enable controlled performance and aging tests of state-of-the-art lithium-ion and sodium-ion cells under forestry-specific duty cycles and temperatures ranging from $-40\text{ }^{\circ}\text{C}$ to $+40\text{ }^{\circ}\text{C}$. Test protocols will be co-developed with machine manufacturers and forest companies to accurately replicate real harvesting and forwarding work cycles, ensuring relevance for mechanized cut-to-length systems operating in boreal climate conditions. Two main experimental blocks are planned: (i) characterisation and performance tests, including pulse-power and representative load-cycle experiments at varying temperatures, and (ii) long-term degradation studies at sub-zero and reference temperatures to quantify capacity fade, power loss and safety-relevant phenomena under realistic use. By generating high-quality, application-specific data, the laboratory will support improved battery integration into harvesting systems, inform cold-mitigation and charging strategies, provide inventory data to support upscaling in environmental and economic analyses (e.g., LCA/LCC) and enable more reliable uptime and lifecycle predictions. Beyond strengthening research infrastructure in northern Sweden, the initiative directly contributes to technological innovation in forest harvesting systems, positioning electrified drivetrains as a viable and climate-resilient solution for future forestry operations.

Keywords: Electrification; Batteries; Cold-climate-operations; Forestry-duty-cycles

Managing moisture content in logging residues through better supply chain planning

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Bioenergy accounts for approximately 30% of Sweden's energy supply, of which about 80% is derived from the forest sector, e.g. in the form of logging residues such as treetops and branches. In recent years, both demand and prices for logging residues have increased in Sweden, driven by societal decarbonisation efforts and ambitions to strengthen national energy independence in response to Europe's security situation. The moisture content in logging residues is a key payment-determining quality attribute, as lower moisture increases energy density in the material and thus its market value. Each year, logging residues worth millions of euros are forwarded from harvesting sites and stored along forest roadsides without any possibility to monitor their moisture content. For fuel suppliers, reliable information on wood fuel stock levels and expected energy content is essential for delivery planning and for fulfilling contractual obligations. Consequently, there is a need for improved understanding of the factors influencing moisture content in wood fuel and for robust methods to estimate it.

Moisture dynamics depend on storage conditions which are strongly influenced by weather-related factors such as precipitation, temperature, humidity and wind. While large-scale weather datasets can explain part of this variation, local microclimatic conditions and practises at the storage site are not captured in the available datasets.

Within the Swedish Energy Agency-funded project "Improved forecasts of logging residues for precision planning", we analysed datasets of wood chip moisture content measured at power plants for thousands of deliveries. The initial aim was to develop a data-driven prediction model to estimate moisture contents and to analyse how storage conditions and supply-chain activities, such as forwarding, could explain the observed variability and provide better decision-support. However, our results showed that forecasting moisture content based solely on available weather data is challenging due to poor representation of local site conditions. It is more effective to promote favourable drying conditions through improved planning and work practices along the supply chain. Enhanced decision-support for moisture management can increase the value of this residual assortment, improve profitability throughout the supply chain and increase overall energy efficiency.

Keywords: bioenergy; heating-value; forwarding; decision-support

A Hybrid Optimization–Machine Learning Framework for Real-Time Dispatching in Forest Transport Operations: A Case Study from Australia

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Efficient dispatching of timber trucks is a major determinant of cost, productivity, and supply reliability in forest transport systems. In operational contexts, where transport distances are long, pickup locations vary daily, and mills operate under strict time windows, dispatching decisions must account for dynamic constraints including queue conditions, service times, driver duty limits, and interactions among trucks competing for shared resources. Traditional truck scheduling models can optimize fleet plans for a full day, but their computational requirements limit their use for real-time decision support when conditions change during operations.

This study presents a hybrid framework that integrates optimization and machine learning (ML) to enable rapid, adaptive dispatching decisions. A fleet-level truck scheduling model is first used as a “teacher” to generate optimized daily schedules across multiple simulated scenarios representing realistic Australian forest transport conditions. These solutions are decomposed into sequential decision points, capturing system state variables such as truck locations, remaining duty time, active transport tasks, origin–destination distances and costs, queue estimates at pickup points and mills, and mill time-window constraints. These data are used to train an ML model that learns to predict the next best transport task for each truck.

Because mill destinations remain relatively stable while pickup locations change daily, the model is structured to generalize across new harvesting configurations. Results indicate that the learned dispatching policy can approximate optimization-quality decisions while operating fast enough for real-time deployment. The proposed approach demonstrates how combining optimization-based planning with data-driven learning can support intelligent, responsive dispatching systems for modern forest transport operations.

Keywords: dispatching; machine learning; optimization;

Real-time monitoring of thinning intensity using harvester data and remote sensing-based single-tree maps

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In thinning operations in rotation forestry, reasonable thinning intensity is key to ensuring favorable development of the stand in terms of sawlog yield, growth loss, and carbon sequestration. In recent years, realized thinning intensities in the Nordic countries have often violated recommended limits, and operators have voiced their desire for decision support and reporting assistance in thinnings. As a response, we present here a new concept, named R-TIM, for real-time monitoring of thinning intensity. R-TIM is based on collecting a remote sensing-based single-tree map of the stand prior to harvesting, constituting a digital twin of the forest. The twin is then kept up to date during the harvesting via matching harvested trees with their counterparts in the tree map using regular harvester measurements and crane-tip localization. Thinning intensity metrics are computed, in real time, for removed tree stock from the harvester data, and for standing stock from the digital twin. We present a case study and evaluation of R-TIM in Finland using real forest data and simulations built on top of these. In addition, we discuss future directions of development and broader implications of the R-TIM concept.

Keywords: operator-assistance; thinning; cut-to-length; simulations

Auto-Annotation Is All You Need? Toward Autonomous Label Generation in Cut-to-Length Forestry

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High-quality, diverse annotations remain a bottleneck for deploying computer vision in

forestry, where scenes are highly variable and targets are defined by operational context rather than appearance alone. A preliminary, fully autonomous dataset creation workflow is presented that links harvester-mounted RGB video to StanForD production records. The pipeline uses visual language models (VLMs) to ground operationally relevant targets in each clip, then applies segmentation with tracking to produce temporally consistent, pixel-accurate instance masks. Because VLM outputs can be non-deterministic, the pipeline includes a consensus-based reliability layer with rejection and fallback logic to reduce grounding errors. The system outputs structured training data aligned with operational metadata and preserves traceability to machine events, enabling reproducible regeneration of labels as models and prompts evolve. Early field-case results are reported for standing trees, a key target in cut-to-length operations.

In an initial clearcutting case study in a pine stand with limited undergrowth, one hour of video processing yielded 52 StanForD-linked cutting events, each represented by a 15-second video clip. The pipeline successfully localized, segmented, and tracked the target tree in 40 of 52 clips (77%). Failures were primarily caused by confusion with high stumps, crane components, stones, and other misdetections. The results indicate that context-aware grounding plus tracked segmentation can generate operationally aligned labels with minimal manual intervention in simple harvesting conditions, while exposing specific failure modes that guide future robustness work.

Keywords: Machine-vision; Dataset; Machine-learning

Productivity and profitability of separate and integrated energy wood and pulpwood harvesting systems under varying stem-size distributions in young stands

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The demand for domestic energy wood and pulpwood in Finland has been high due to the increased use of forest chips and the cessation of wood imports from Russia. The forestry operations in the supply chain still face a persistent and long-standing challenge: young, often untreated first-thinning stands are characterised by high stem densities and small-sized harvested trees, which result in low hectare-based removals and quality products, generally pulpwood and energy biomass. This, in turn, lowers forest machine productivity and increases harvesting costs, highlighting the need for improved harvesting systems and solutions, and accurate productivity estimates of those systems.

The objective of this study was to examine the time consumption, productivity, and profitability of two harvesting system alternatives for those stands, and namely: separate or integrated harvesting of the two main products (e.g. pulpwood and energy wood). For the test, we used an excavator-based system (Doosan DX140 LCR-5) equipped with a TMK-300 felling head for whole-tree harvesting and Ponsse Ergo 8w/H7, Ergo 6w/H6, and Fox/H5 harvesters adapted for multiple-tree handling through dedicated software.

Time study data were collected from five forest stands. In total, 4,519 stems (309.1 m³ [solid over bark, sob]) were harvested with harvester-based systems and 3,210 stems (49.4 m³ sob) with excavator-based systems. The harvesting systems tested were:

- 1) Whole-tree harvesting,
- 2) Delimbed stem wood harvesting,
- 3) Pulpwood harvesting (using single-tree cutting & multiple-tree handling), and
- 4) Integrated energy wood (delimbed stem wood) and pulpwood harvesting with two-piles cutting.

When the size of removal was 5–13 cm (diameter at breast height), the effective hour productivity (E0) was 0.3–11.8 m³/h with separate whole-tree cutting and 0.4–19.3 m³/h with separate delimbed stem wood cutting. Correspondingly, the productivity of separate pulpwood cutting using single-tree and multiple-tree handling was 0.3–17.3 m³/h and 0.5–18.3 m³/h, respectively. With integrated delimbed stem wood and pulpwood cutting, using a two-pile method, the productivity was 0.4–17.8 m³/h. Cutting and extraction costs were calculated, and the profitability and sensitivity of different harvesting systems under various stand characteristics were examined and discussed.

Keywords: costs; first_thinning; multiple-tree_handling; wood_fuels

The filtering effect of unsealed pavements at storage yards for leachate from wood chip piles

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Seepage water can occur when wood chips are stored outdoors. In relation to precipitation, the amount of seepage water is small. It contains high levels of dissolved organic matter. If such water enters surface waters, it could pose a threat to aquatic life. If the water seeps into humus-rich forest soils, microorganisms decompose the dissolved organic matter of the water quickly and thus filter them out. Unsealed pavements at storage yards don't have a humus-rich and biologically active soil layer. Until now, the filtering effect of a storage area ground was unclear. To investigate this, wood chips were piled up on a gravel storage area and seepage water was collected and analyzed using lysimeters both above and below ground to a depth of 30 cm.

The experiment showed that the COD values (chemical oxygen demand) of the seepage water were significantly lower than in previous experiments. The values in the subsoil did not differ significantly from those on the surface. The BOD and TOC values (biological oxygen demand and total organic carbon) were also low. The reasons for the low COD values are not entirely clear. Possible influencing factors include the smaller size of the wood chip pile, dilution by precipitation water, biological degradation during the retention time in the collection container, and binding to calcium in the filter material of the lysimeters, although only a minor effect could be detected for the latter. No significant filtering effect of the subsoil was observed. There is no danger to soil organisms above the groundwater line from the seepage water because there is sufficient oxygen available. As a precautionary measure, it is recommended not to store wood chips outdoors at sites with very high groundwater levels.

Keywords: Bioenergy; storage; leachate

Timber transport – national analysis of road-related delays and underlying causes

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More competitive wood supply is dependent upon increasing load sizes for timber trucks. With a background of increasing precipitation and temperatures the latest revision of Norwegian forest road standards have been adapted with improved construction and drainage specifications. However, the existing forest road network has been constructed over a time span of 60 years, throughout the evolution of truck combinations to the current 60t/24m standard. At present both 65, 68 and 74t truck-trailer combinations are being run on a test basis in Norway.

With this background, road upgrading investments require documentation of priorities for effective transport operations. The goal of the study was therefore to map out the key challenges of today's forest road network from a transport availability perspective. The purpose is to map out the most critical factors for improving road availability and competitive roundwood transport.

The study provides a national analysis covering both lowland and mountainous topographies on the eastern- and western sides of the Scandinavian mountain range. The first part presents the results of focus group interviews mapping the key dimensions of current challenges (30 trucking companies). The second part presents a quantitative analysis of transport messaging during 2024 and 2025 reporting i) noncompliance with road standards and ii) consequent delivery delays (all Norwegian wood supply organizations).

The quantitative analysis is enabled by new functionality in the forest sector transport system (SkogData VSYS-transport). The existing transport messaging (PapiNet std) includes load-level data such as wood order/transport order identification, time stamp, origin-destination coordinates, loaded transport distance, public road standard (GVW class), wood assortment code and load volume. Since 2024 noncompliances have been registered within the same system. The noncompliance category for forest roads includes 6 sub-categories: bearing capacity, road width, road grade, landing grade, roadside vegetation and insufficient snow removal/sanding (with explanatory free text). Noncompliances are linked to a secondary function for resulting transport order delays («TO parking»). TO delays have 6 sub-categories of underlying factors: public roads, private roads, forest roads, delay until improved bearing capacity, delay until road/turnaround is improved, and other factors (eg. receiver status).

In this presentation the STT project (STT; Forest road conditions and availability) reports seasonal distributions and durations for 33 000 non-compliances and 15 500 delivery delays during 2024 and 2025. AI-assisted interpretation of free text descriptions provided a more detailed distributions of underlying factors. These are seen in the context of risk evaluations by 30 transport companies, where seasonal transport conditions vary considerably between coastal and interior regions.

Keywords: roads, logistics, information systems

Hyperspectral imaging for forest seedling quality assessment: a review

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One of the most important parameters for the successful establishment of forest stands and forest habitat restoration programs is forest seedling quality. Some of the traditional methods for seedling quality assessment are invasive, time consuming, and labor-intensive. Hyperspectral imaging, in contrast, provides a noninvasive evaluation method, making it a new and a promising tool for seedling quality assessment. This is crucial from aspect of practical nursery production and outplanting success, but also as an background for development of new scientific methods. By capturing hundreds of continuous spectral bands, HSI enables the detection of detailed plant traits. This review focuses on the application of HSI in assessing forest seedling quality for application in nurseries and after outplanting in the frame of restoration initiatives highlighting its strong potential for evaluating key parameters. However, HSI alone cannot capture dimensional/physical traits, such as shoot height, root mass, bud dormancy, and therefore is best used in combination with complementary technologies, including LiDAR, vegetation indices, and image-based methods. This review also examines current challenges in implementation of HSI in operational nursery settings, such as illumination position sensitivity, plant-specific traits, large data volume, and high equipment cost. By integrating hyperspectral plant phenotyping and nursery practices, this review identifies future directions for HSI implementation in forest seedling production, thereby supporting more efficient nursery settings.

Keywords: hyperspectral; seedling; noninvasive; nursery

Digital Support for Smart and Safe Motor-Manual Harvesting

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Despite increasing fully mechanized timber harvesting, motor-manual operations are still required, for example for the selective removal of high-value individual trees, in sensitive stands or difficult terrain, in calamity patches, or in small private forests. Besides physical strain, these motor-manual tasks entail an elevated accident risk for workers, caused for instance by deadwood, limited experience in assessing trees, or unsuitable choice of tools. While the flow of information along the wood value chain is already digitally supported in harvester–forwarder systems through standards such as StanForD2010, ELDATsmart, or papiNet, many steps in motor-manual harvesting are still recorded by hand and are frequently passed on with media discontinuities.

The research project SmaSiKaFE (Smart and Safe Calamity Area Harvesting) addresses these challenges in motor-manual timber harvesting and designs a continuous digital process. Forest workers are provided with a smartphone app that supplies the necessary information and offers recommendations for safe felling and value-optimized bucking. Using the app, work progress can be documented and transmitted to downstream actors.

The technological basis for data exchange is the Smart Forestry concept, which follows the Industry 4.0 approach. A so-called Asset Administration Shell (AAS) enables standard-compliant data exchange along the entire value chain. The AAS represents physical objects (forest stands, machines, stem sections etc.) as digital twins, encapsulating their data, functions, and parameters and thus enabling manufacturer-independent interoperability. Data is exchanged in a decentralized, trustworthy, and protected way via a messaging hub, the Smart Systems Service Infrastructure (S³I).

Digital work orders can be created using standard software connected to the AAS. In addition to the task description, aspects of work organization as well as emergency numbers and rescue points can be specified, which users can directly view or dial in an emergency.

For the safe felling of backward-leaning trees with wedges or winches, estimating the tree's center of gravity is crucial. The proposed method records a point cloud of the stand via terrestrial laser scanning, either in advance of harvesting or continuously during routine work. Individual trees are extracted from the point cloud, followed by spatial recognition of stems and branches and automatic detection of possible damage (e.g., crown or stem breakage). The stem is then decomposed into segments to which typical density values are assigned, allowing the center of gravity to be derived. This information is provided in the app via the tree's digital twin, enabling the calculation and display of the required forces, attachment heights, and insertion depths of auxiliary equipment. As an alternative to laser scanning, photo-optical methods for determining tree parameters are considered, which may be particularly advantageous in small private forests.

Based on the tree data, precise suggestions for assortment bucking can be generated from the taper curve and actual stem form, analogous to harvester-based optimization. After felling and processing, stem sections and work progress are recorded in the app; the data is transmitted back, updates the virtual stand, and forms the basis for subsequent extraction and logistics.

Keywords: Forestry-4.0; digital-workflow; digital-twin; point-cloud-analysis

Battery Electric Vs. Diesel in Forestry Transportation: A Performance Comparison of Timber and Wood Chip Trucks

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In countries with a large forestry sector, road transportation is responsible for a considerable fraction of territorial carbon dioxide emissions. At the same time, heavy road freight in rural areas is arguably one of the most challenging cases for electrification. In the project TREE: Transition to efficient electrified forestry transport, 12 fully battery electric roundwood and wood chip trucks are studied during 18 months of operation. The feasibility and success of any means of transportation must be evaluated from its role in the logistics system. One component of evaluating the electric trucks of the TREE project is a 1:1 focus study, where each truck was compared to a corresponding diesel truck, with respect to energy use and productivity. We also observed the drivers' different experiences from the two types of trucks. The trucks were set up to perform as similar transportation missions as possible in a two-day study. On the first day, the trucks worked tightly in pairs to closely replicate the physical conditions (time of day, driving pattern etc.) during loading and driving. On the second day, the trucks carried out the same transportation missions, but the drivers were free to work as best suited the respective truck's conditions. The comparisons show that, depending on the mission, the electric truck can in some case replace a diesel truck without much adaptation whereas in other cases, it is difficult to match the productivity of the diesel truck. More importantly, the focus study will support the understanding of how electrification might influence forestry transport operations.

Keywords: electric; timber; chip; truck

Estimating the Availability of Forest Biomass for energy considering the introduction of trailers into winding road networks in mountainous areas of Japan

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This study estimated the availability of unused materials for woody biomass power generation plants registered in FIT (Feed-in Tariff) as the supply potential through the introduction of trailers with 20-t payload instead of trucks with 10-t payload which were widely used on winding road networks in mountainous areas of Japan. As a result, supply potentials of used and unused materials were estimated at 65,413,601 m³/year and 13,082,720 m³/year, whereas those availabilities were estimated at 64,322,304 m³/year and 12,864,461 m³/year, respectively. Therefore, the rate of the availabilities to the supply potentials was 98.3%. The availabilities of used and unused materials without the introduction were 54,268,941 m³/year and 10,853,788 m³/year. Thus, its introduction contributed to increase the availability. Since the demand of woody biomass power generation plants registered in FIT was estimated at 11,018,104 m³/year, the availability through the introduction met the future demands in Japan as a whole.

Keywords: FIT; Payload; Supply potentials

Operational decision-support for prioritizing wood transports using AI and digital twin data

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Uncertainty in harvesting output and road accessibility significantly affects supply chain planning and the ability to meet customers' demand for high-quality wood products in a timely manner. Despite a long-term harvest scheduling, variations in product volumes can reduce delivery precision and increase the risk of product backorders. Weather conditions also influence landing accessibility; for example, schedules based on expected road conditions may suddenly change due to warmer weather, thawing, or heavy rainfall.

In response to these challenges, there is interest in modeling variations, such as predicting road accessibility, which is further stressed by climate change. Predicting product variations and road accessibility can support forest managers in operational planning; however, decision-making on transport prioritization must remain aligned with planning objectives to ensure that established delivery performance targets are met. Evaluating road accessibility is an important tool, but it should be complemented by decisions on transport prioritization to meet delivery goals, such as minimizing backorders and delivery variations.

To address this problem, we present a methodology that uses an AI agent for decision-making on transport prioritization, fed with data from a digital twin to monitor landing inventory levels and road accessibility. Despite operational variability, the agent's goal is to prioritize transports to maintain adherence to multiple long-term delivery targets.

The methodology is implemented in a decision-support prototype that enables managers to track long-term planning goals on a dashboard and to evaluate how operational decisions based on predicted road accessibility and real-time landing inventories align with delivery targets. The dashboard visually helps identify landings at risk of reduced road accessibility and provides guidance on prioritizing transport. It also supports the comparison of alternative decision scenarios, helping managers determine when a new long-term harvest schedule may be needed.

The prototype is expected to be further developed and integrated into operational environments in future projects in collaboration with forestry stakeholders.

Keywords: digital twin; decision support

Data-Driven Analysis of Forest Operations in Steep Terrain Using Integrated Machine and Remote Sensing Data in Japan

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Digital technologies are increasingly transforming how forest operations are monitored, analyzed, and optimized. In Japan, forest harvesting is often conducted under challenging conditions characterized by steep terrain, fragmented harvesting areas, and hybrid operational systems that combine mechanized harvesting with manual work. While mechanization has advanced in recent years, operational decision-making and productivity evaluation still rely heavily on experience-based assessments, and the growing volume of digital machine data remains largely underutilized.

This research explores the integration of multiple digital data sources to improve the analysis of forest harvesting productivity and operational safety. The study combines onboard machine data, in the form of StanForD production files, with GNSS tracking of field operations and high-resolution environmental information derived from drone-based LiDAR. By synchronizing these heterogeneous datasets, the approach enables detailed analysis of how terrain conditions, forest structure, and operational practices influence machine performance and work processes.

The integration of machine, worker, and environmental data provides a framework for spatially explicit and process-oriented evaluation of forest operations. Such data-driven analysis supports the identification of productivity drivers, the detection of safety-critical operational patterns, and the development of improved work planning strategies. In addition, the use of remotely sensed LiDAR data allows the operational context, such as slope, stand density, and tree dimensions, to be directly incorporated into performance analysis.

The outcomes of this research contribute to the development of data-driven forest operations by demonstrating how existing digital information streams can be combined to support objective productivity assessment and safer working conditions. By linking operational data with environmental information, the study provides insights relevant to forestry companies, researchers, and policymakers seeking to advance smart forestry practices and sustainable forest utilization under diverse field conditions.

Keywords: LiDAR; GNSS; Mechanisation; Steep terrain

Session 5

Potential Areas for Ground Lichen–Adapted Young Stand Management in Northern Sweden: A Case Study

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Modern Swedish forestry has contributed to a substantial decline in ground lichen, a key winter forage resource for semi-domesticated reindeer, while demand for timber and bioenergy continues to increase. This study develops and tests a generic, easily implemented GIS-based screening method to identify priority areas for lichen-adapted young stand management that can simultaneously support biomass utilization and reindeer husbandry in northern Sweden.

We conducted a case study on productive forest land owned by Sveaskog, overlapping the Ubmeje Tjälldie and Vapsten reindeer herding communities. The analysis was restricted to productive forest land, as only these areas are subject to regular management operations. Stand data included 32,347 stands (309,476 ha), of which 20,200 stands (237,372 ha) were classified as productive forest land. Young stands were defined as those with a need for pre-commercial thinning, initial thinning, or complementary thinning (management classes 21, 31, 32), while stands treated with fertilizer were excluded due to known negative effects on ground lichen.

We combined corporate stand data with spatial datasets on lichen coverage (10 m raster, continuous % cover), soil moisture (2 m, categorical), and management history (polygon attributes). Ground lichen potential was quantified by aggregating the lichen raster to stand level using a hierarchical threshold system inspired by the Swedish National Forest Inventory, but with expanded classes tailored to reindeer grazing needs. First, we calculated the proportion of pixels with $\geq 10\%$ lichen cover and assigned stands to five lichen cover classes, recognizing that $< 10\%$ cover is too low to be of grazing relevance. Second, we calculated the proportion of pixels with $\geq 25\%$ lichen cover and grouped stands into four additional classes to highlight areas with higher forage quality. Third, we recorded the presence/absence of pixels with $> 50\%$ cover, treating these as “hotspot” indicators due to their low frequency but high value for grazing.

This multi-threshold approach generates stand-level indicators describing both the extent and intensity of lichen occurrence, enabling screening of a wide combination of stands for lichen-adapted management. The resulting indicators can be used to rank and map priority stands for young stand treatments that increase light availability and improve accessibility, such as boom-corridor thinning and geometric thinning systems. These methods have shown potential to increase mechanized harvesting productivity in dense young stands, offering opportunities for additional biomass recovery while improving conditions for reindeer.

Ongoing work compares the mapped priority stands with an independently developed list of stands prioritized through a collaborative planning process between Sveaskog and the reindeer herding communities. This comparison will be used to validate the method’s relevance for operational co-planning at both stand and landscape scales. The proposed framework is replicable, relies on commonly available stand registers and remote sensing products, and can be scaled to other reindeer herding districts. It therefore offers a practical decision-support tool for integrating lichen-oriented, adaptive young stand management into forest operations while contributing to a growing bioeconomy.

Keywords: Precision-forestry, Remote-sensing, GIS, Adaptive-management

A GNSS-Derived Digital Twin of Forestry Road Networks for Two-Stage Trucking Productivity Modelling

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Two-stage trucking systems in New Zealand forest harvesting operations have become increasingly common, with their adoption rising from 8% to 24% since 2016. Despite this growth, productivity modelling research remains largely reliant on elemental time studies, which typically generate small datasets covering only several days of work. This study presents an automated, data-driven framework for constructing a digital twin of forest road networks and applying it to two stage trucking operations to model truck productivity over extended periods.

Controller Area Network bus and GNSS position data were collected from a two-stage truck operating in the Hawke's Bay region of New Zealand over a 230-day period across two harvesting sites. Latitude, longitude, altitude, and truck pitch data were filtered, resampled, and projected to a metric coordinate system. A raster-based skeletonisation approach was applied to buffered GNSS traces to reconstruct road centreline geometry. The extracted network was segmented into road sections and attributed with geometric properties including gradient, curvature, and length.

The segmented road network enabled each GNSS point to be mapped to a corresponding segment, allowing precise identification of truck position within the network. A segment-based state logic integrating road geometry and CAN data was developed to classify operational states (loading, driving loaded, unloading, driving unloaded, and idle). This allowed the capture of individual cycles without having to manually delineate the data depending on which landings the truck loaded or unloaded from. Segment-level metrics—including speed profiles, tonnage carted, and cycle times—were derived and linked to network topology to model productivity.

Results demonstrate that the digital twin road network and segment-based state logic enables productivity modelling without reliance on pre-existing GIS datasets or manual elemental time studies. The proposed method supports automated cycle detection, road topology performance benchmarking, and scenario testing for two-stage transport planning optimisation. The method could also be integrated into a live dashboard for real-time analytics and tracking of trucks during their operations.

Keywords: Two-staging; Roading; Productivity; Digital-Twin

Real-time optimal bucking based on 2D-projected mobile laser scanning data

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Forest harvesting operations increasingly require real-time, non-destructive tree-level information to support precision decision-making directly within machine workflows. Although harvester-mounted Mobile Laser Scanning (MLS) systems provide detailed three-dimensional representations of tree stems, most existing processing approaches depend on full point cloud reconstruction, frame alignment, and Simultaneous Localization and Mapping (SLAM). These pipelines are computationally demanding and typically require post-processing, limiting their applicability for real-time decision support in operational environments. Consequently, sensing, measurement, and bucking optimisation are often addressed as sequential and loosely connected tasks, constraining the development of fully integrated, sensor-driven harvesting systems.

This study presents an integrated real-time framework that operates directly on raw MLS data through two-dimensional projections of individual MLS frames, thereby avoiding explicit 3D reconstruction. Each frame is independently transformed into a structured 2D representation that enables stem instance segmentation using a 2D Convolutional Neural Network (CNN). From the segmented projections, geometric attributes such as stem diameters and longitudinal profile are estimated sequentially, allowing the progressive construction of a dynamic stem representation during machine operation. These measurements are directly coupled with an optimisation module implementing an optimal bucking strategy based on predefined product specifications and operational constraints. By integrating perception, measurement, and optimisation within a unified continuous processing pipeline, the proposed framework establishes a reconstruction-free approach to real-time, sensor-driven bucking decisions and contributes to advancing automation in forest harvesting systems.

Keywords: Precision_harvesting; Optimal_bucking; LiDAR; Instance_segmentation

The effect of cutting technique on the mortality and resprouting vigor of hybrid poplar stumps

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Short-rotation coppice is a modern industrial crop, and its profitability depends on the mechanisation of all management operations. Once the crop is mature, trees can be felled with a variety of machines, but shears represent the most effective solution. However, shears can cause some stump damage, raising concerns about stump mortality and re-sprouting vigor, both crucial to coppice regeneration. This study, conducted at five sites in western Slovakia, compared the mortality and resprouting vigor of stumps cut with shears and chainsaws, the latter representing the control treatment. Measurements were taken on 6 compartments across these sites. In each compartment, between 9 and 10 sample plots were established, each consisting of two parallel row segments containing 10 live stumps (20 stumps per plot). One row segment was cut with a shear-type felling head, the other with a chainsaw-type felling head. One year after cutting, we assessed stump diameter, number of live shoots, and diameter and height of the 5 tallest shoots. Data were pooled into a structured database and statistically analysed. The results of the study showed that site fertility had a very strong effect on resprouting vigor; the method of the cutting technique did not affect survival stumps, but shear-type cut stumps produced slightly more shoots, and dominant shoots on shear-cut stumps might grow more slowly due to stronger intra-stump competition, especially in less fertile sites.

Keywords: Cutting¹; Effect²; Mortality³; Stump⁴

CEFOR – Modernizing Forest Operations and Securing the Future Workforce

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Forest operations are a cornerstone of the forest-wood sector, mobilizing tens of millions of cubic meters of wood each year. These resources serve multiple societal needs: timber for construction and furniture, industrial wood for paper, cardboard, and panels, and energy wood for heating and biomass. Sustainable forest management ensures that forests continue to provide these resources while preserving ecosystems.

Over the last 25 years, forestry has become increasingly technical and complex. Modern machinery now integrates digital technologies, GPS systems, and advanced harvesting tools. Scientific research has improved our understanding of how machinery impacts soils and forest environments, while regulations and certifications have strengthened sustainability standards. Market demands are also evolving, with growing opportunities in industrial wood and bioenergy, which require operators to adapt continuously.

Despite these advances, the sector faces a serious challenge: a shortage of young, trained professionals. Even the most advanced machinery and innovative techniques cannot reach their full potential if there are no skilled people to operate them. Young professionals are crucial not only to handle technical equipment but also to apply best practices, respect environmental standards, and innovate in response to societal expectations. Without them, efficiency, safety, and sustainability are at risk.

CEFOR (Common Digital Knowledge Base for Forest Operations) addresses this challenge directly. It provides a structured, practical, and accessible digital platform covering eight key thematic areas, from planning and site preparation to harvesting, transportation, and safety management. By presenting processes chronologically, CEFOR makes complex operations easier to understand and apply in real-life scenarios.

Developed with forestry professionals, CEFOR ensures that all content is both technically accurate and pedagogically relevant. Its goals are to train newcomers in modern forestry techniques, improve operational performance, and support sustainable, responsible forest management in line with environmental and climate goals. Case studies from real worksites help learners see the diversity of challenges and career paths in forestry.

CEFOR also serves as a tool to attract new talent. By showcasing the technical nature of modern forestry, the skills required, and the use of advanced machinery, the platform aims to inspire young people to consider careers in this essential sector. Partnerships with training centers, professional organizations, and cooperatives ensure wide accessibility and integration into education and professional development programs.

In short, CEFOR is more than a digital resource—it is a strategic solution to two critical challenges: the increasing technical demands of forestry and the urgent need to attract and train the next generation of professionals. Without a skilled workforce, even the most advanced equipment cannot be used effectively. By providing practical, structured, and accessible knowledge, CEFOR ensures that forest operations remain efficient, safe, and sustainable, while securing a workforce capable of meeting the challenges of tomorrow.

Keywords: Training; platform, attractiveness; forest

Reliability of Receiver-Reported GNSS Accuracy in Forest Conditions

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Receiver-reported Global Navigation Satellite System (GNSS) accuracy metrics (e.g., horizontal accuracy estimates derived from solution covariance) are sometimes used as proxies for positional reliability in forestry applications. However, their predictive validity under canopy and obstruction remains insufficiently quantified. This study evaluates the relationship between receiver-reported accuracy and empirically observed positioning error across four static environment classes representative of forestry sector conditions.

Static occupations were conducted on pre-surveyed control points in forest interior, forest edge, tree-adjacent, and building-adjacent environments. Horizontal error was quantified using Distance Root Mean Squared (DRMS), the average value for stand conditions reaching 2.3 meters. Error distributions were strongly non-normal in all environments (Shapiro–Wilk $p < 0.001$). Correlation between reported accuracy and DRMS was highly environment-dependent. In dense forest interior, linear predictive power was negligible ($R^2 = 0.002$; Pearson $r = -0.05$; Spearman $\rho = 0.14$). At forest edge, explanatory power remained minimal ($R^2 = 0.005$; Pearson $r = 0.07$; Spearman $\rho = -0.44$). In contrast, minor associations were observed in building-adjacent ($R^2 = 0.10$; Pearson $r = 0.32$; Spearman $\rho = 0.51$) and tree-adjacent conditions ($R^2 = 0.19$; Pearson $r = 0.44$), indicating partial covariance tracking under certain obstruction geometries.

Despite these differences in correlation structure, receiver-reported accuracy systematically underestimated empirical error in all environments. Median DRMS exceeded reported accuracy by factors ranging from approximately 2.6 (forest edge/tree-adjacent) to 8.0 (forest interior/building-adjacent). Dispersion inflation under severe obstruction was not proportionally reflected in reported accuracy metrics.

Dynamic measurements across 13 operational environment classes further demonstrated horizontal degradation relative to open-sky conditions and consistent vertical error inflation. Dynamic horizontal receiver-reported accuracy ranged from 273 mm in unobstructed locations to 758 mm in forested environments with vertical obstructions, while vertical accuracy varied between 397 mm and 1333 mm across the same conditions. These values highlight the impact of vegetation, vertical structures, and terrain slope on the GNSS solution's reported accuracy, and suggest that even when absolute positioning errors differ, reported precision can serve as a relative indicator of environmental complexity affecting receiver performance.

These findings indicate that receiver-reported GNSS accuracy exhibits environment-dependent predictive validity but consistently underestimates true positional error magnitude in obstructed forest conditions. Reported accuracy metrics should therefore be interpreted cautiously and not as absolute values. Given the generally weak or negligible linear correlations in highly obstructed environments, these metrics cannot be reliably corrected or rescaled to match true error; simple multiplicative adjustments will not produce accurate positioning estimates, they may however find a use as relative or qualitative metrics.

Keywords: forestry; mechanization; gnss; accuracy

RoadSens: A Mobile Sensing Platform for Forest Road Digitalization, Classification, and Operational Decision Support

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Reliable and up-to-date forest road information is essential for sustainable forest operations, affecting technical road classification, timber transport accessibility, and maintenance planning. However, conventional road inventories are often incomplete, outdated, and costly to maintain due to their reliance on manual surveys and expert assessments. Over the past four years, we have developed RoadSens, a mobile proximal sensing and analytics platform designed as a technical solution for comprehensive forest road digitalization, enabling multiple operational applications from a single data acquisition workflow. This contribution synthesizes the development, methodological advances, and validation of the RoadSens platform.

RoadSens as a flexible to use vehicle attachment, integrating stereo vision spatial mapping, deep learning-based perception, and precise geo referencing through the fusion of post processed GNSS and stereo derived odometry. The platform provides a detailed geometric description of forest roads, including longitudinal slope, horizontal and vertical curvature, and cross sectional parameters such as road width, centerline position, sidefall slopes, and ditch characteristics. Validation across several forest roads in Norway demonstrates that the platform is capable of delivering consistent, spatially continuous geometric information suitable for operational use.

This geometric foundation enables multiple downstream applications. First, RoadSens supports automated technical road classification according to defined road standards, using geometry based criteria such as slope, curvature, and width. Case study results indicate that road width is often the dominant constraint in meeting technical standards, underlining the value of systematic and up to date geometric data. Second, RoadSens provides essential input for operational planning, including the assessment of accessibility and restrictions for timber trucks, by delivering road parameters relevant for vehicle performance and safety. Third, the platform has been extended towards maintenance planning through automated detection and mapping of surface deterioration features, which are aggregated into intuitive, segment level maintenance indicators.

Across all applications, the main current bottleneck is not the sensing or geo referencing concept, but the performance of object detection models used for road surface interpretation. While technically feasible, detection of irregular and heterogeneous deterioration features remains challenging. Importantly, this limitation is primarily data driven and can be systematically addressed through larger, more diverse, and higher quality training datasets, making the approach well suited for continuous improvement as additional data become available.

Overall, RoadSens demonstrates the potential of mobile sensing as a scalable and cost effective alternative to manual forest road surveys, providing a unified data basis for technical classification, operational planning, and maintenance decision support.

Keywords: proximal-sensing; road-geometry; deep-learning; maintenance;

An innovative shear-based solution for bucking logs for energy production

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The economic sustainability of energy-oriented forest supply chains depends on the ability to process low-value biomass using robust and cost-efficient technologies. In such contexts, reducing maintenance requirements, minimizing downtime, and maximizing operational productivity are essential to maintain profitability. Conventional grapple-saw systems, although widely adopted, are primarily designed for higher-value assortments and may not represent the most efficient solution when bucking material destined for energy production. This study evaluates a radio-controlled shear prototype powered by an autonomous 89 kW engine, designed to provide a simple and robust bucking system for low-value biomass assortments. Field trials were conducted in aged chestnut coppice stands, where whole logs were bucketed at a landing into two target lengths (2.4 m and 6 m), comparing the shear prototype with a conventional grapple-saw. When bucking to 6 m lengths, the shear prototype achieved a productivity of 10.21 m³ h⁻¹, approximately 49% higher than the grapple-saw (6.85 m³ h⁻¹). Bucking to shorter 2.4 m lengths reduced productivity by 29% for the shear prototype and by 53% for the grapple-saw, highlighting a greater sensitivity of the conventional system to shorter assortments. Fuel consumption per unit volume was reduced by approximately 58% at 6 m and 76% at 2.4 m with the shear prototype compared to the grapple-saw. The results demonstrate that shear-based bucking provides a technically reliable and advantageous alternative for low-value biomass, combining higher productivity with substantially lower fuel use, thereby reducing operational costs and improving the overall efficiency of energy-oriented harvesting operations.

Keywords: prototype; shear; productivity; grapple-saw

TECHNO-ECONOMIC COMPARISON OF TWO MECHANISED SHRUB HARVESTING SYSTEMS FOR BIOENERGY PRODUCTION

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The energy utilisation of shrub biomass requires specialised machinery adapted to shrubland conditions, enabling efficient harvesting and collection in cost-effective formats suitable for energy production. Proper handling is essential to minimise soil contamination and ensure the production of high-quality biofuels. Current harvesting technologies integrate clearing and biomass collection into a single operation, producing either baled or mulched material, each associated with distinct logistical requirements within the biomass supply chain.

This study presents a comparative analysis of mechanised shrub biomass harvesting using two different machines associated with different logistics systems: a López Garrido TBA-2300 harvester-mulcher and a Biobaler WB55 harvester-baler. The techno-economic evaluation was conducted in a natural mountain shrubland dominated by rockrose (*Cistus laurifolius* L.) in Soria (Spain). This species commonly occurs in association with oak, pine and holm oak forests on acidic or decalcified calcareous soils. In the Iberian Peninsula, rockrose occupies 51,377 ha as a dominant species and 680,856 ha as a secondary species (San Miguel et al., 2004; Montero et al., 2020), extending across wide areas of the central-northern, eastern and southern regions.

The López Garrido TBA 2300 harvester-mulcher, powered by a 200 hp forest-adapted tractor equipped with a reverse driving position, is driven by the power take-off and hydraulic system and has a working width of 2.3 m. Biomass is shredded by mobile hammers and conveyed by a screw and turbine into a 5 m³ front container for temporary storage. In contrast, the Biobaler WB55 performs shrub cutting, collection and baling in a single operation with a similar working width (2.3 m). The harvested biomass is compacted into cylindrical bales (Ø 1.2 m), automatically tied and discharged at the rear, facilitating handling, transport and storage.

The mechanised harvesting trial was designed to assess weight productivity (tWM/PMH, tonnes of wet matter per productive machine hour), area productivity (ha/PMH), operational costs (€/tWM) and harvesting efficiency (CE, %), defined as the ratio between collected biomass and the biomass available prior to harvesting. Operational times were recorded using the Valtra Connect telemetry system installed in the tractor, allowing remote monitoring of productive working hours, travelling speed, fuel and additive consumption, and spatial tracking of the operated areas.

Under similar stand conditions, the harvester-mulcher achieved significantly better performance than the harvester-baler. Biomass recovery reached 3.9 tWM/ha compared with 1.3 tWM/ha, while productivity was 1.4 versus 0.5 tWM/PMH. Harvesting efficiency was also higher (82% compared with 52%). These differences translated into substantially lower collection costs, with biomass harvested using the harvester-mulcher costing 48 €/tWM compared with 192 €/tWM for the baler, and productive hourly costs being 22% lower (82 €/PMH versus 105 €/PMH).

For biofuel production, the material was ground using a 30 mm screen and sieved through a 2 mm mesh to reduce fines. The resulting hog fuel was classified as class I1 according to ISO 17225-9. Rockrose represents a low-cost solid fuel characterised by low emissions of NO_x, SO₂, HCl and minimal slagging, but its high ash content makes it more suitable for industrial than residential applications.

Keywords: Harvester-baler; Harvester-mulcher; Scrub; Biomass

LEARNING CURVES OF SKILL ACQUISITION IN VIRTUAL ENVIRONMENTS FOR BASIC OPERATION OF HARVESTERS AND FORWARDERS

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The need for safe, efficient and standardized training methods has promoted the use of virtual reality simulators as an alternative tool to conventional training, especially in high-risk operational industries. These simulators allow technical skills to be developed while reducing operating costs, physical and environmental risks, and machinery wear, and facilitate the controlled and safe repetition of tasks. In this study, the evaluation of the learning process and the acquisition of technical skills were analyzed through individual and group learning curves, with execution time as the main performance indicator for skill acquisition. Ten trainees with no previous experience in forestry machinery voluntarily participated in basic scenarios on a Komatsu simulator for harvesters (gripping and felling) and forwarders (loading and unloading). The aim was to develop basic operational skills, promote familiarization and adaptation, and teach control commands. The training consisted of a total of ten repetitions per trainee distributed across the six scenarios of varying complexity and duration. Exponential learning models were used to model the performance evolution, as they best fitted to the data, demonstrating that completion time-based learning was non-linear. The results showed a rapid and steep initial improvement followed by a phase of deceleration and progressive stabilization. Scenarios with greater complexity or those with longer execution times presented curves with slower stabilization and greater interindividual variability, suggesting greater cognitive and psychomotor demands, while scenarios with shorter execution times showed faster adaptation with less dispersion. All six scenarios showed a common pattern of individual and group learning with a progressive decrease in time through practice repetitions. These findings support the integration of virtual reality technologies, especially simulators, into training programs and the use of learning curves as a tool to evaluate performance improvements.

Keywords: ``Virtualreality; simulator; learningcurves; training"

LiDAR technology as the basis for designing forest roads

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The labor shortage is becoming a growing problem in the European forestry sector. As current data collection techniques rely on field labor, data collection for the purposes of forest road design is more difficult than in the past. For that reason, there is a need to identify more efficient field data collection method. The previous method of field data survey in forest road design process was based on the use of classical survey methods (theodolite and level) and modern survey methods (total station). The mentioned methods provide sufficient accuracy during survey but are time-consuming and required a large number of auxiliary workers. The quantity of collected field data that classical and modern field survey methods enable us to do are incomparable to the quantity of spatial data collected by LiDAR sensors. LiDAR survey could eliminate the problem of labor shortage and the and reduce the time required to collect field data. The aim of the research is to determine the applicability of collecting field data using LiDAR sensors and the influence of vegetation on the results of field measurements in the process of designing and developing the main project for the reconstruction of a forest road. The research was conducted regular forest stand in moderately steep terrain of Republic of Croatia, the main tree species in the research area are: *Fagus sylvatica* L. and *Quercus petraea* Liebl.. Two different LiDAR survey method were tested: using an unmanned aerial vehicle (ALS) and airplane (ALSDGU). Based on the collected field data, two versions of the forest road reconstruction main/implementation designs were developed. Total length of reconstructed roads was 44+93.18 hm. Based on the main projects of the researched forest road, the amounts of earthworks required for its reconstruction were calculated. The research determined the level of influence of vegetation on the accuracy of the tested measuring equipment, which provided new insights and guidelines for choosing the most suitable method of collecting field data when designing forest roads.

Keywords: Forest infrastructure; ALS; TLS

Digitalization in forestry: a user-centered approach to developing a mobile app for cable yarder layout

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Forest cable yarders are a highly effective timber extraction system, particularly in steep mountainous terrains. Operating these systems demands high expertise, as does the preliminary planning and ground layout of the lines. Accurate field tracing and post-installation verification are critical to ensure technical feasibility (e.g., maintaining ground clearance for suspended loads) and operational safety regarding tensions and payload capacities. Traditionally, in Italy these operations are carried out directly by forest operators, except in the most complex cases where surveying relies on professional technicians conducting field visits. However, involving external technicians incurs additional costs and logistical delays for forestry companies. Conversely, when operators conduct the surveys without specialized tools, formal safety and documentation requirements are often not fully met. Therefore, there is a clear need to simplify this phase, and digital instruments offer highly functional solutions. While the digitalization of the forestry sector has led to a rapid proliferation of mobile applications, there remains a distinct lack of tools specifically tailored for the fast, simple, and immediate surveying of cable yarder lines. This study presents the development of a novel application for smartphones and tablets—named “Teleferika”—distinguished by its innovative, iterative design approach driven directly by the practical needs of forest operators. The development process began with a targeted questionnaire administered to experienced operators and forestry instructors. This user-centered approach directly informed the developers about the core functionalities to be implemented in the app. Primarily, the app allows operators to easily record fundamental line characteristics (such as anchor points and intermediate supports) during the layout and installation phases. The app was equipped with an intuitive graphical interface featuring real-time cartography, effectively functioning as a navigation system along the theoretical line. The collected spatial data can be exported in standard formats (.shp, .kml, etc.) and transmitted via email or messaging platforms to off-site technicians. They can then generate formal site documentation and perform rigorous payload verifications using specialized software like Seilaplan. Moreover, the initial operator survey revealed a strong demand for a modern alternative to the traditional compass for field tracing, an operation the app was expected to perform effectively and improve. In this sense, initial field testing alongside operators highlighted the inadequate accuracy of standard smartphone GNSS receivers. To resolve this, the system was integrated with low-cost RTK-GPS antennas, successfully refining positioning accuracy to approximately 1 meter. Throughout the development process, the application underwent multiple iterations based on continuous operator feedback. Finally, to ensure true practical viability, comprehensive usability tests were conducted. These trials not only identified the system's strengths and limitations but also provided valuable insights into the operators' reception of new technologies and their overall readiness for the digitalization of the forestry sector. In this contribution the development process and the results of both the functional and usability tests will be shown in detail.

Keywords: “Cable-yarder-layout; Digital-forestry; User-centered-design; Usability.”

Different Wood Damages from Seven Harvesters

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In Sweden, approximately 75 million m³ of timber are harvested each year, predominantly using single-grip harvesters. Maintaining wood value is essential, and the process begins already at the harvesting stage. The Wood Value Trials is a Swedish comparative study evaluating seven large harvesters from different manufacturers. Each machine felled and processed 30 Norway spruce stems, producing roughly 150 logs per harvester. This study is a part of that trial and focuses specifically on wood damage arising during bucking. It is important to minimize damage levels, as part of the wood is wasted at the saw mill if containing bucking splits, stud- or debarking damage, affecting the economic value.

The three types of wood damage were studied separately:

Splits resulting from bucking were assessed at both ends of each log, except at the butt end of the first log (the felling cut). Splits were measured by cutting discs with a chainsaw, striking the lower third of each disc to detect any hidden splits, and continuing to cut discs until the split terminated. The total split length was calculated by summing up the thickness of the discs. The radial position of the split was recorded as the distance from the log center.

Stud damage caused by the feed rollers was recorded at the top end of the log. Damage depth was measured by cutting across a stud mark with a knife and measuring, in millimeters, the deepest affected fiber.

Bark peeling caused by the delimbing knives was recorded at the top end of the log. The extent of bark damage was measured by placing a measuring tape around the log's perimeter and recording the width of the peeled area. Damage was classified as either 50% depth or 100% depth (the latter indicating complete removal of inner bark and exposure of wood).

Differences in damage levels were compared among the seven harvesters. The preliminary results indicate differences between all three damage types, suggesting that harvester head design has a measurable effect on wood value. These findings imply that further technical development of harvester heads is important to improve value recovery and reduce revenue losses associated with wood damage.

Keywords: Harvester; Value; Bucking; Damages

MECHANIZED PIT-DRILLING COST – A SIMULATION STUDY TO ASSESS THE EFFECT OF PLANTING SCHEME AND PLOT SIZE FOR TWO TRACTOR CLASSES IN POPLAR FOREST ESTABLISHMENT OPERATIONS

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The practice of poplar forest establishment, maintenance, and harvesting varies globally, potentially inducing significant effects on cost structures and environmental impacts. In Romania, for instance, a typical life cycle involves operations such as ground clearing, stump removal, soil milling, pit drilling, and manual planting, followed by several cultivation stages, thinning, and clear-felling. While mechanized pit drilling is not a new option, modern machinery has seen significant technical and operational improvements. In this study, we utilized an extensive GNSS-annotated dataset collected from two tractor classes during pit-drilling operations. Specific events - including entering a row, drilling a pit, moving between locations, re-entering maneuvers, and relocation - were documented at one-second intervals. These data were used to extract event durations and frequencies to compare the performance of the two tractors. Given the non-normal nature of the data, bootstrapping was employed to infer the mean values and compare differences at the event level. Our findings suggested significant performance differences between the tractors, which were subsequently treated as two distinct options for cost assessment. The cost assessment integrated detailed statistics on fixed, variable, and labor costs. Using performance metrics such as event duration and speed, we conducted a cost simulation driven by plot size (1 to 20 hectares), variable plot dimensions, and four common planting schemes (5 × 4, 4 × 4, 4 × 2, and 3 × 2 m), resulting in nearly 84,000 comparison datasets. We evaluated two unit cost metrics: cost per pit and cost per hectare. Performance strongly influenced outcomes; the larger tractor class yielded higher unit costs, likely due to increased maneuvering and inter-pit travel time. Within the same tractor class, unit costs increased non-linearly with plot width, reflecting the impact of frequent entry and exit maneuvers relative to shorter on-row operations. When analyzed against plot length, costs were largely clustered by plot size, with cost differences becoming most pronounced for plots up to 5 hectares. These results provide updated performance and cost figures for poplar establishment in Romania. Furthermore, they demonstrate that the current practice of clear-felling in plots up to 5 hectares represents an economically critical threshold, beyond which cost reductions become marginal. Internationally, our findings illustrate how plot geometry and planting schemes drive costs, supporting the selection of optimal tractor classes for specific site conditions.

Keywords: Establishment; Drivers; Trends; Economics

Guidance counsellors strengthening the attractiveness of the forest sector – Preliminary results

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In Finland, the forest sector currently needs and will continue to need new workers. With demographic development, the age groups are becoming smaller and more urbanized, which means that young people may not have any contact with the forest sector before applying for education. Previous studies have emphasized that students' perceptions of different educational paths and occupations can be easily influenced by prejudices. For some young people, the forest sector still appears conservative, traditional, and masculine. The forest sector is still highly gendered. Additionally, according to the previous studies, raising awareness of the forest sector is essential for young people to be able to apply for training in the field. Strengthening the attractiveness of the forest sector is important in preventing future labor shortages. Study counselling is a free-of-charge support included in education in Finland that helps students plan their studies, choose their education, get to know the working life, and plan their careers. The purpose of study guidance is to promote justice, equality, and inclusion. The criteria for good guidance state that it is multidisciplinary cooperation that supports the development of career-planning skills.

This study examined guidance counsellors' attitudes and knowledge regarding the forest sector. In addition, the study was conducted to determine how guidance counsellors perceive young people's interest in the forest sector. The data were collected through interviews in the autumn of 2025. In total, 49 guidance counsellors participated in the interviews, 23 of whom worked in general upper secondary schools and 26 in comprehensive schools.

Based on the preliminary results, the interviewees were very familiar with the educational opportunities in the forest sector. However, awareness of working life came to the fore, which should be given attention in the future. In addition to telling students about their studies, sharing concrete career stories, work tasks, and working weeks should also provide young people with information about what it means to work in the forest industry. The guidance counsellors emphasized that communication about the forest sector should be based on encounters between people. Despite this, almost half (47 %) of schools represented in the study had received a visit in the previous 12 months from a forest-sector organization, educational institution, forestry student, or other representatives to provide information about education and working life in the forest sector. Furthermore, 61 % of the general upper secondary guidance counsellors and 65 % of the comprehensive school's guidance counsellors interviewed perceived the forest sector positively. Only two counsellors (4.1%) expressed a negative attitude towards the forest sector. The guidance counsellors perceived forests as highly or very significant, both at the individual level and for Finnish society.

Keywords: forest labor, forest education, guidance counsellor, working life

Keywords: Keyword1; keyword2, keyword3, keyword4

Using UAV-Based Remote Sensing Techniques for Allocation of Drainage Structures on Forest Roads

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The presence of standard-compliant forest road networks is essential for the sustainable management of forest ecosystems and the efficient execution of forestry operations. Enhancing the resilience of these roads to environmental impacts, preventing water erosion, and extending their service life depend on positioning engineering structures at the optimal topographic locations along the route. Identifying the locations of these structures using conventional ground-based surveying techniques is a labor-intensive, time-consuming, and costly process. This study aims to determine the optimal locations for the engineering structures required on forest roads using unmanned aerial vehicle (UAV) photogrammetry. Within the scope of the research, UAV flights were conducted in selected study areas to acquire high-resolution aerial photographs. These images were processed using photogrammetric software to generate digital elevation models (DEM) and orthomosaics. Based on the generated data, hydrological and geomorphological analyses were performed in a geographic information systems (GIS) environment to identify the locations of the drainage and retaining structures. The points obtained from the analyses were validated in the field, and the reliability of UAV technology as a decision support tool in forest road infrastructure planning was evaluated. The findings indicate that UAV photogrammetry provides data in a shorter time, at a lower cost, and with higher spatial accuracy compared to traditional methods. The study concludes that UAV technology is an effective decision support tool that saves time and labor in the process of identifying engineering structures.

Keywords: Precision forestry, Road infrastructure

Enabling Resilient Forest Value Chains through Physical-Digital Continuity: Integrating StanForD, Single Tree Marking, and EBSI Blockchain

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Digitalizing the forest supply chain is essential for building resilient value chains that can handle increasing regulatory and environmental complexity. However, implementation is currently hindered by fragmented systems and breaks in communication between harvesting, logistics, and processing. The lack of integration, which is often caused by proprietary data formats, undermines the digital continuity required for transparent operations and compliance with stringent mandates such as the EUDR and the Digital Product Passport (DPP).

To address these challenges, this study proposes an innovative approach to ensure interoperability using the international StanForD standard. The solution involves integrating robust Logscam colour-spray modules directly into harvester aggregates or the forwarder's stake grid. These modules automatically apply alphanumeric identification codes to the cross-cut section of the timber and creating a persistent physical-digital link. This mechanical application is designed for the harsh environments of forestry operations, ensuring resilience against weather and handling.

By linking machine-independent data, including georeferenced harvest locations, dimensions and species, to each unique log, the system enables seamless traceability. Upon arrival at the sawmill, the markings are captured via automated optical recognition, linking the physical material back to its digital twin. To guarantee maximum data integrity and proof of origin, selected datasets are secured via EBSI blockchain notarization. This end-to-end integration eliminates manual documentation errors, strengthens the resilience of the chain of custody and provides a scalable foundation for a sustainable, verified forest-based bioeconomy.

Keywords: Digital Continuity; Resilience; DPP

Modelling the Influence of Cutting Dynamics on Bucking Splits

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Efficient bucking systems and careful timber handling are key factors in maximizing timber value. To evaluate the performance and long-term advancement of such systems, Skogforsk has conducted a series of large-scale wood value trials. The most recent study, conducted in 2025, compared seven leading harvester systems under operational conditions. Data were collected in a spruce-dominated final felling stand in central Sweden, which resulted in several complementary datasets used to study dimension measurement accuracy, bucking performance, positioning, timber handling, and system functionality according to StanForD 2010.

The present analysis examines how cutting dynamics influence the occurrence of bucking splits, which are caused by the gravitational forces acting on the freely hanging part of the log during the cut. Cutting time was determined from high-speed video recordings of cuts across a representative range of log diameters, and a comparison with cutting speed data from previous wood value trials will be presented. The video material was further used to describe the progression of the cut with regard to saw bar angle. Measurements of bucking splits were performed on the bucked logs from 210 stems. Discs were manually cut from the log ends and struck until breakage, allowing classification of the break as either natural or the result of a bucking split based on characteristic patterns.

A logistic regression model was developed to relate cutting dynamics to the likelihood of bucking splits. The model incorporates cutting time, saw bar angle, and log geometry to mechanistically capture the interplay between stress development and cut progression, which determines whether the cut is completed before split-inducing stress levels are reached. Preliminary analyses indicate that log geometry is the dominant factor explaining the occurrence of bucking splits, while aspects of the cutting process also show statistically significant effects.

Keywords: harvesting; timber-value; harvester-head; structural-mechanics

Are young people interested in forestry jobs?

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The aim of this contribution is to present the analysis of the professional interests and motivations of young people regarding forestry careers. An online survey (N = 162) was conducted in May 2025. The study identifies the profile of a typical forestry candidate as an individual from a rural area, men or women, who prioritizes job security and personal satisfaction over high financial reward. The findings confirm that while forestry students show the strongest interest in jobs in forestry, intrinsic motivation and a personal relationship with nature are the primary drivers across the board. The key results indicate that practical field experience and communication with forestry professionals significantly increase career interest. Furthermore, the emerging generation of foresters demonstrates an "ecologically realistic" perspective, favoring sustainable management and biocentric values over traditional paradigms. The study suggests that to combat the declining workforce, forestry communication should leverage these intrinsic values and increase practical engagement during university studies. Respondents assigned the greatest importance to statements reflecting biocentric and ecocentric values, emphasizing the intrinsic value of forests, ecosystem impact considerations, and their role in environmental balance and human well-being.

Keywords: "Employment", "Education", "Students", "Motivations"

LoRaWAN IoT system to improve safety operation in remote steep slope harvesting?

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The study will present the implementation of a smart monitoring system based on LoRaWAN technology to support the improvement of safety and operational efficiency in cable yarding on steep slopes.

As a case study area, a typical harvesting intervention with cable yarder in the Italian prealps was chosen.

An LTE-enabled LoRaWAN gateway was mounted on the tower yarder to ensure a stable wireless communication across the harvesting site, with a theoretical data transmission capacity of the payloads up to 1 km away from the gateway itself. Preliminary network coverage analyses were performed in GIS to investigate how terrain morphology interacted with the signal transmission. To this, a detailed methodology involving the use of visibility analysis tools allowed to evaluate areas potentially lacking network coverage. The methodology was then validated on field with a two-antenna GNSS-RTK system exchanging corrections with LoRa transmission protocol.

Then, high sensitivity motion sensors, including inclinometers and accelerometers, were installed on key structural components, including the carriage, tail anchor tree, and tail spar, to measure inclination and rotational movements under working conditions. Specific warning and critical thresholds were defined to detect abnormal movements and potential instability. An automated alarm system was integrated with a Telegram chatbot to provide real-time notifications to operators.

The preliminary results confirm the feasibility and robustness of the solution and open to a wider discussion on LoRaWAN technology applied to monitor and connect forest operation in real time also in complex mountain terrain. Canopy occlusion was confirmed not to be a factor correlated to the signal quality. Transmission of the payloads were possible up to 500 m from the tower yarder. Further improvements as the use of a directional antenna, or changing the SDR of the radio transmission may further extend this approach to even longer distances.

Keywords: cable-yarder; communication; monitoring; safety

Value recovery in modern CTL harvesters - a large scale practical test

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Skogforsk has carried out reoccurring tests of harvesters with a focus on value recovery (including e.g. damages, measuring accuracy, optimization efficiency) and StanForD implementations since the mid 1990's. A new test with seven different final felling harvesters was carried out in the autumn of 2025 in one single location north of Uppsala. The test was carried out in a Norway spruce stand with an average stem size around 0.9 m³sub where each machine harvested at least 220 stems and 34 of these stems were manually control measured. The test also included, for the first time, an evaluation of the precision of stem coordinates from harvesters equipped with high precision GNSS systems.

All active manufacturing members in the StanForD working group were invited to participate. The following harvesters participated:

Base machine Harvester head Controller

Komatsu 951 C144 MY23 MaxiXT

Rottne H21 EGS706 Dasa Forester H70

Ponsse Scorpio Giant New Ponsse H7 Opti 5G

EcoLog 590G Ec661 Lf Dasa Forester H70

Logset 12H Logset TH80 TOC-MD

JohnDeere 1470H H425 Timbermatic H

Tigercat 1165 Log Max 5000V Log Mate 510

It is possible to analyze the historical development of several key figures as this type of test has now been carried out five times with the same basic methodology. The presentation will thus include comparisons between the harvesters in the present test as well as general comparisons over time.

The presentation will include results on length, diameter and volume accuracy for the different harvesters where manual control measurements are used in order to compare with the values generated by the harvester. Results on the performance of the bucking optimization will also be presented including the effect of the measuring errors. All harvesters today have the possibility to use two different optimization methods and results for both methods are thus included in the study. The overall trend is that the measuring accuracy has improved since the previous test (e.g. standard deviation for diameter measurements has decreased from 2,3 mm to 1,4 mm since the test 2006) and that the bucking optimization algorithms are performing as expected (≈99% of theoretical maximum).

The test also included a thorough analysis of the implementation of the StanForD standard including what data is available from each control system and what StanForD version that is supported. Three of the harvesters had implemented the latest StanForD version (4.1) which enhance the reported production data, especially when it comes to positioning information such as the log positions. Another important aspect was to test and verify that the flexibility in controlling the bucking optimization works

as expected, e.g. making it possible to change the mix of assortments or species harvested at a specific site.

Three harvesters reported the true position of the stem and most machines could report tracking data describing machine movements. All systems support registering “stem codes” that makes it possible to identity e.g. retention trees and wind-throws.

Other aspects such as precision of stem positioning, processing damages and sawing speed will be covered in other presentations at the conference.

Keywords: harvesting; value-recovery; measuring; optimization;

Retention by design? A longitudinal evaluation of a work-based forest machine operator apprenticeship in Aotearoa New Zealand

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New Zealand's forest harvesting workforce faces persistent retention challenges. The lack of clear forestry career paths, poor employment conditions, and limited awareness of opportunities have contributed to retention rates of only 30% after three years in the forestry industry (MPI, 2019; Workforce Insights, 2022). In a highly mechanised sector where operator capability is central to productivity and safety, low retention undermines both workforce sustainability and the return on training investment. This paper reports interim findings from a longitudinal evaluation of a work-based operator apprenticeship scheme that has achieved markedly higher retention than the wider industry.

The programme is delivered through an employer-integrated apprenticeship aligned to NZQA training requirements (NZ Certificate in Forest Harvesting). It combines structured block-course delivery, theory completion support, and practical on-the-job development, supplemented by simulator-based training and exposure to downstream supply chain requirements. The evaluation design follows successive cohorts over time, using repeated semi-structured interviews at key milestones (programme entry, end of theory blocks, completion of practical requirements, and post-completion follow-up). Interview recordings are analysed using template analysis to identify mechanisms that support skill development, job fit, and commitment to the industry, alongside barriers that reduce perceived value. Evaluation findings are triangulated with programme tracking data on completion and retention and with employer feedback.

Across five cohorts to date, programme tracking indicates completion/continuation rates of approximately 77% (30 of 39 participants) and industry retention of approximately 85% (33 of 39 participants), including evidence that some non-completers remain in the industry and some withdrawals re-enter the programme after re-employment. Participant accounts suggest that perceived value extends beyond technical skill acquisition to include clearer pathways and credentials, structured support to complete theory, increased understanding of "why" operational practices exist (including customer requirements) and strengthened social connection through cohort learning in an otherwise isolated industry. The least valued element is classroom-based "book work," pointing to ongoing tensions in how theoretical components are delivered for a practically oriented workforce.

These interim results indicate that a workplace-embedded apprenticeship can function simultaneously as (i) a skills development pathway, (ii) an induction and socialisation mechanism, and (iii) a recruitment/selection filter that improves job–person fit—together contributing to substantially higher retention than sector benchmarks. Implications are discussed for designing operator development systems that strengthen both workforce capability and workforce stability in mechanised harvesting.

Keywords: Operators; apprenticeship; work-based; retention

Session 6

A Multi-Criteria Decision Support System for Sustainable Timber Harvesting System Selection

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Selecting a timber harvesting system is a context-dependent decision that requires substantial expertise to balance economic performance, environmental impacts, operator safety, and technical feasibility. In practice, system choice is influenced by stand and site conditions (e.g., slope, extraction distances, soil conditions), machine characteristics and operational constraints, and trade-offs between sustainability dimensions are inevitable. This work presents the concept and architecture of a decision support system (DSS) that supports harvesting planners in selecting the most sustainable harvesting system – i.e., machine combinations for felling/processing and extraction – for a given stand.

The DSS follows a multi-criteria decision analysis (MCDA) framework. Sustainability is represented by nine core criteria operationalized through 15 indicators covering the three pillars (economy, environment, social/work safety). The workflow comprises seven steps: (1) User Input: scenario definition (stand, site, operation) and criteria weighting, (2) configuration of potential machine chains, (3) feasibility screening, (4) calculation and harmonization of indicator values using an evidence-based data layer, (5) transformation of indicators into normalized utilities, (6) weighted aggregation into overall scores and rankings, and (7) reporting of machine chain ranks and trade-off visualizations.

The MCDA framework is underpinned by a data layer that provides reference values and parameter-dependent ranges for indicator estimation, while feasibility screening uses these operating envelopes to constrain system recommendations under the specified conditions. Using this foundation, a combination of data-driven and process-based models is employed to derive indicator values from user-defined stand and operational inputs. These indicators form the basis for multi-criteria evaluation and optimization, allowing machine chain alternatives to be assessed and ranked according to trade-offs between economic, environmental, and social objectives. The relative importance of these objectives can be adjusted through user-defined criteria weightings, allowing the system to reflect different stakeholder priorities and decision contexts. The overall aim is to generate context-specific machine chain recommendations that balance sustainability dimensions in timber harvesting operations.

Our contribution highlights the modular system design (data layer, rule layer, formal model and user interface) and discusses open research needs, in particular systematic evidence expansion, harmonization standards, and the derivation of a minimal dataset to guide future field data collection and model calibration.

Keywords: DSS; Sustainability_Indicators; Harvesting_Systems; Criteria_Weighting

Planting spot quality and regeneration success with a less intensive drill-based soil preparation method: A feasibility study

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The positive effects of soil preparation on the survival and growth of planted seedlings have been widely known for a long time. However, recent studies have highlighted the importance of developing new technical solutions for soil preparation to mitigate its harmful environmental impacts. For example, particular interest has fallen upon methods that reduce the intensity of soil disturbance yet still provide favorable growing conditions for seedlings.

A novel and less intensive drill-based soil preparation device was recently developed in Finland. The drill significantly reduces soil disturbance compared to conventional methods, such as disc trenching and mounding. However, the performance of the drill and its effects on forest regeneration success have thus far remained unexamined.

In this study, we established five experimental sites in eastern Finland to evaluate the feasibility of drill-based soil preparation for planting conifer seedlings. The aim of the study was also to provide practical knowledge for the further development of the device. First, we assessed the quality of the planting spots (N = 4120) created by a crawler excavator fitted with the drill-based device. Secondly, we evaluated the early performance of Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) seedlings that were planted throughout the growing season following soil preparation.

Based on our feasibility study results, the drill primarily resulted in good (61%) and satisfactory (34%) planting spot quality. We found that the presence of stumps, roots, logging residues, and stones decreased the spot quality. Two years after planting, Norway spruce seedlings were, on average, more viable than those of Scots pine. Site fertility and seedling vitality were significant predictors of Norway spruce height. However, further research is needed on the factors that influence seedling survival and growth when using a drill-based soil preparation method.

Keywords: site preparation; soil disturbance

When Culture Meets Hazard: Habitus, Stress and Coping in the Logging Workforce of Aotearoa NZ

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Overseas studies and emerging data from within Aotearoa New Zealand indicate that those working in forest environments experience a significantly elevated risk of suicide. Yet the limited research conducted within global forest industries has primarily focused on psychosocial conditions and their health impacts, under-recognizing how structural and cultural forces interact to shape workers' responses to stress and distress.

This presentation offers an explanatory account of how stress and wellbeing are constructed by logging machine operators, drawing on constructivist grounded theory to centre the lived experiences of 27 participants. The analysis demonstrates that wellbeing arises from the dynamic interplay between an operator's habitus, the embodied dispositions, values, and cultural logics shaped through the logging lifeworld, and the structural determinants of the psychosocial conditions they face. This challenges the prevailing assumption that mental health outcomes in high-risk industries can be understood primarily as responses to environmental stressors, showing instead that they are culturally mediated and shaped by how operators navigate production pressures, hierarchy, identity, and control.

This reframing responds directly to the conference theme of enabling resilience through innovation by demonstrating why effective suicide-prevention and wellbeing initiatives must address both structural determinants and the cultural logics that shape coping. It highlights how the same psychosocial environment can produce markedly different wellbeing outcomes depending on the operator's habitus and their position within the crew and contracting hierarchy.

This perspective provides a foundation for co-designing interventions that are both culturally grounded and structurally informed. A brief case example, drawn from a separate study that developed a video-based operator training system, illustrates how centring operator habitus and lived experience can inform more effective, context-aligned intervention design. Together, these insights offer a reframed understanding of suicide risk in forestry and point toward innovative, lived-experience-led approaches to prevention in high-risk work settings.

Keywords: Operators; psychosocial; interventions; resilience

Branch-aware tree stem optimal bucking using splines and graph-based segmentation

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Precision forestry seeks to improve the sustainability and efficiency of forest management by applying new technologies to characterise individual trees. Accurate tree-level characterisation, typically through remote sensing, facilitates optimising timber yield and minimising waste. To that end, optimal bucking methods can be applied given accurate enough estimates of tree features. Among these features, stem shape and branching patterns are critical for stem bucking, as they determine the wood quality and the dimension and amount of products obtained. Yet, deriving this information from 3D point clouds remains challenging due to noise, non-circular cross-sections, and the difficulty of separating stems from branches.

In this study, we developed a novel stem shape characterisation and bucking method for tree point clouds capable of accounting for noisy data and irregular or curved trunks. Furthermore, we integrated tree branching information to estimate branch insertion points, find co-dominant or forked trunks, and gauge crown size. To do so, we leveraged graph theory to segment tree branches and isolate stem points. We then fit robust splines recursively across and along the stem, capturing curvature and irregular growth patterns through a recursive procedure. The resulting stem geometry and branching metrics served as inputs to the optimal bucking algorithm. We validated the proposed method on simulated point clouds, as well as LiDAR data acquired using a Mobile Laser Scanner (MLS) in Outokumpu, Finland. Our method successfully integrates branching patterns into bucking solutions, advancing tree-level decision-making. Moreover, it provides valuable insights into tree morphology for forest resources and biodiversity inventorying.

Keywords: LiDAR; bucking; segmentation; reconstruction

Timber Harvesting Challenges on Small Family Forests in Northern Minnesota, USA

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One-third of forestland ownerships in Minnesota are comprised of privately-owned, family forests. The majority (65%) of those family forests are found on less than 8-hectare parcels and the owners of which commonly have alternative land stewardship objectives that differ from traditional forest management goals. Timber harvesting as a management objective is universally low in priority for small family forest owners, yet it is often still required to achieve many of the landowner's other stewardship objectives. A logging business owner makes various decisions based on economic factors when considering a timber sale purchase; but they may also consider other factors particular to their business characteristics. All these considerations become increasingly important as the size of a timber sale decreases and may become barriers to implementing a timber harvest on small family forests.

Northern Minnesota logging business owners were surveyed to collect individual business-specific data regarding factors affecting their decisions to purchase small-sized timber sales, barriers to harvesting timber on small tracts, and the general characteristics of their business. Results suggest that some logging businesses may be more readily adaptable to harvesting on small family forests. A logging business whose annual production was <3,625 cubic meters and used a chainsaw as a primary felling method was the most likely to purchase a timber sale of 725 cubic meters and less. While they generally target purchasing higher volume timber sales, larger producing businesses annually complete more of these small sales than the smaller logging businesses. The most important factor for a larger logging business' consideration to purchase a small timber sale is whether the sale is adjacent to another larger and available timber sale. If the family forest tract is not adjacent to another timber sale, the lowest volume producers appear to be the most likely to purchase the sale.

Keywords: Landowners; adjacency; production; chainsaw

An Operational Analysis of Salvage Logging using Cut-to-Length Harvesting in the Southeastern United States Following Hurricane Helene

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Weather events such as tornados and hurricanes can significantly impact forest stands and create operational challenges for harvesting and utilization. Rapid salvage following events is critical in the southeastern US due to the onset of insect damage and wood discoloration due to blue stain fungus. In September 2024, Hurricane Helene impacted the region as a Category 4 hurricane, with recorded wind speeds of up to 225 kph. The storm caused an estimated 2.6 billion USD impact to the forestry sector in the state of Georgia alone. The urgency of salvage operations makes it difficult to study harvesting productivity, cost, and value recovery resulting in a significant need to better understand effective forest management strategies post-disaster. This study aimed to evaluate the use of cut-to-length harvesting systems in these unique conditions. Specific objectives were to assess individual machine and system productivity, system cost, and the effect of differing tree damage classifications on harvester productivity. We selected two loblolly pine (*Pinus taeda*) stands in the lower Coastal Plain physiographic region of Georgia, USA, that sustained significant damage from the hurricane. We conducted time studies of a Ponsse Ergo harvester and Elephant forwarder. Data collection consisted of an elemental time study for the three main functions: felling-processing, forwarding, and loading. Time study data combined with stem volumes from onboard computers and load weights from mill scale tickets were used to estimate individual machine and system productivity. Results indicate that overall system productivity was 14.19 m³ SMH⁻¹, onboard truck cost was 16.03 USD m⁻³ and cut and haul costs were 24.03 USD m⁻³ which is competitive with published rates for the region. This study provides insight into the feasibility of using CTL harvesting systems in challenging salvage logging conditions following storm events and will aid forest managers and logging contractors in understanding productivity and cost expectations.

Keywords: Salvage; Cut-to-length; US; Productivity

Impact of Additional Restrictions on Nesting Time of Birds on Wood Procurement in Finland

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The Birds Directive protects wild bird species, their habitats, and prohibits deliberate disturbance during the nesting season. Forest operations—particularly timber harvesting—during the nesting season may have negative impacts on bird habitats, breeding success, and populations. The recent decision of the EU Court of Justice creates a need to specify and clarify national regulations regarding logging practices during the breeding season also in Finland.

In Finland, the nesting season typically extends from April to July, although its exact timing varies by region and species. Limiting logging, forest management, and regeneration activities during this period would have substantial implications for forest management practices, the forest industry, and the availability of wood for industrial processing and energy use.

Wood harvesting in Finland is seasonal, with a greater emphasis on the winter season. Additional restrictions during the nesting season would further intensify this seasonality, increasing the demand for forest machines and their operators during a short winter window. Timber storage needs would rise, affecting an increase in costs of harvesting, logistics and storage. Concurrently, there would be an increase in winter transport volumes, thereby amplifying seasonal pressure on timber trucks and labour availability.

We examined the impacts of harvesting restrictions during bird nesting-season on wood supply, forestry operations, and the forest industry in Finland using predefined scenarios. These scenarios were compared with a baseline to assess cost impacts, labour and machine demands, and effects on production volumes and value added in the wood-processing industry.

Scenario analysis of the most extreme change scenario showed that eliminating all summer logging would increase the unit timber harvesting and storage costs (incl. logging, trucking and storage costs) by around 6% and reduce annual wood harvesting by approximately 25%, resulting in substantial economic impacts.

In an alternative scenario where 50% of the harvesting potential during the nesting season were shifted to harvest to winter (January–March), the unit harvesting and storage costs would increase by around 17%. This shift would require an additional 3,723 operators (including harvester, forwarder, and timber truck operators) and 2,383 additional machines and vehicles during winter.

The least disruptive scenario involved reallocating harvesting of broadleaved-dominated sites and spruce-dominated bogs to winter. This option increased harvesting and storage costs by only 2.7% compared to baseline scenario. This scenario would align with national recommendations from the forest industry and the Finnish FSC standard, as well as with the current legislative proposal in Finland.

It should be noted that not all the scenarios studied are feasible, or their implementation would require significant changes in wood procurement practices, business operations, and the availability and stability of the workforce. The most challenging factors mentioned are the limited availability of skilled labour for short-term seasonal work and the difficulty of running a profitable and sustainable harvesting business in such a seasonal sector. Additionally, a critical factor is the impact of increased

logistics costs on stumpage prices and the availability of wood, as well as on the competitiveness of the forestry industry.

Keywords: ``harvesting"; "trucking"; "seasonality"; "scenario-analysis"

EXPERT-BASED ERGONOMIC RISK ASSESMENT IN MECHANIZED FORESTRY TRANSPORT OPERATIONS

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improving productivity and operational efficiency. However, despite increasing levels of mechanization, transport-related activities such as log extraction, uphill hauling, load stabilization, and auxiliary water transport continue to expose workers to significant ergonomic and safety risks. Challenging terrain conditions, whole-body vibration, repetitive movements, awkward postures, and time pressure contribute to musculoskeletal disorders and long-term occupational health problems in forestry operations.

This study proposes an expert-based ergonomic risk evaluation framework for mechanized forestry transport activities. Rather than relying solely on accident statistics or large-scale datasets, the research emphasizes structured expert judgment and systematic risk scoring to identify and prioritize critical ergonomic hazards in field operations.

In the first stage, a panel of forestry engineers, machine operators, and occupational health and safety specialists was consulted to identify key ergonomic risk factors. These factors included posture load, repetition frequency, manual force exertion, vibration exposure, slope gradient, task duration, and environmental constraints. A structured evaluation form was developed based on these parameters.

In the second stage, ergonomic risks were assessed using the Hazard Rating Numbering System (HRNS). Each transport task was evaluated in terms of severity, exposure frequency, and probability. Risk scores were calculated and classified into risk categories (low, medium, high, and very high). This approach enabled systematic prioritization of transport-related activities under mechanized forestry conditions.

The findings indicate that tasks performed on steep slopes, repetitive hose handling in water transport, and manual-assisted log stabilization present the highest ergonomic risk levels. Whole-body vibration and prolonged static postures were identified as critical contributing factors. Expert consensus emphasized the need for ergonomic redesign of operator cabins, improved vibration damping systems, better task rotation planning, and slope-adaptive operational planning.

The proposed framework provides a practical and implementable decision-support tool for forestry managers without requiring complex data infrastructure. From a forestry mechanization perspective, integrating structured expert judgment into risk assessment contributes to safer operational planning, reduction of musculoskeletal disorders, and sustainable workforce management.

This study highlights the importance of proactive ergonomic evaluation in mechanized forestry systems and demonstrates how expert-based assessment can support safety-oriented mechanization strategies in challenging field environments.

Keywords: Forestry; Ergonomics; Risk; Safety

Small-scale forest owners' perceptions and use of digital decision support: attitudes, needs and barriers

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In Sweden, half of the forestland is owned by approximately 300,000 individual private forest owners. In total, they spend about 11 million work hours per year on forest management activities in their forests. Each to fulfill their own personal goals with forest ownership. Typical activities are planting, pre-commercial thinning and undergrowth clearance. Contractors are often hired for logging, meaning that forest owners also are customers of forestry services and need to evaluate who to contract and be able to assess the services provided. Today, this is often done subjectively and not based on objective information. This not only risks poorer target achievement for the procured services, but also generally gives an incomplete picture of service quality. Many of today's private forest owners lack forestry education and experience but are motivated to take advantage of most of the forest's values and protect high cultural and environmental values. One way to make it easier for small-scale forest owners to make good decisions and achieve high goal fulfillment is to innovate and implement new user-friendly tools such as digital decision support. The objective of this study was thus to identify and quantify the needs for digital decision support that can improve forest owners' purchasing skills when procuring forest services and facilitate the implementation and evaluation of forestry activities they carry out themselves. Data on forest owners' current perceptions and use of digital decision support was collected through a questionnaire that was sent out to 1495 randomly selected non-industrial private owners in Sweden. The response rate was about 25% (n=366). The results show that about one third of the responding forest owners today use digital decision support for one or several purposes. The most common use was when assessing the need for forestry management measures on the forest property, and as a support when contracting service providers. About 40% of the users used digital decision support when following up on actions taken or as support when carrying out forestry work themselves. Almost as many used it for selecting the best management option based on their goals. Most users experience that digital decision support saves them time compared to other approaches, and that it contributes to better decisions and increased quality. Among non-users, it was more common for them to feel that they lacked the necessary skills to use digital decision support than that their use would be limited by a lack of technical conditions. Moreover, many non-users did not believe that digital decision support would make it easier for them to adapt their forestry to their goals. The study concludes that there is great potential to increase the use of digital decision support among small-scale forest owners, but that both educational and information efforts are needed to increase knowledge and raise awareness of the existence and benefits of these tools. By highlighting the needs of different types of forest owners, this study can contribute to the development of practically applicable digital support systems that can simplify and rationalize the forest owner's work.

Keywords: NIPF; Survey; Digitalization; Forestry

Developing digital solutions for efficient forest road maintenance between multiple owners

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Norway has a forest road network of 50 000 km, where a single road typically has 4-5 owners. The current road network has been progressively extended since the 1960s. As a result of climate change and transition to heavier timber trucks, maintenance practices are becoming increasingly important.

Over the last decades there has been increased focus on cooperation between forest owners and road owner associations. This led to the development of road maintenance associations to coordinate tasks and maintenance between road associations across administrative borders. The activities for the maintenance associations drive task planning, cost distribution and accounting through a web-based platform (<https://vfvweb.no/>).

The VVM project (Road Maintenance module) aims to develop the next generation of web-based solutions for road- and road maintenance associations, to support a gradual upgrading of forest road standards. The current accounting platform has been in operation since 2008 and includes a historical database of maintenance activities and cost categories. The database spans 17 maintenance associations with 11 000 maintenance tasks across 458 roads and 1471 forest owners. The current management practices have been mapped at three stakeholder levels, and improvement potentials are identified.

One of the project goals is to ensure the dissemination of knowledge on effective summer maintenance and their costs. This presentation focuses therefore on the analysis of task-specific cost development from 2008 to 2024 from one region of southeastern Norway. The results support road owners in making realistic plans for maintenance tasks and budgets. It also documents the effects of cooperation through road maintenance associations road maintenance cost levels.

Keywords: Information-systems; Cost-development; Cost-distribution; Cost-accounting

Evaluation of harvester positioning capabilities and practical use of positioning information

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Modern cut to length (CTL) harvesters increasingly incorporate positioning information as part of their standard data output. This information ranges from machine traces that continuously log machine movement, to base machine positioning during felling, to the positioning of stumps and, ultimately, each processed log. While high accuracy GNSS receivers with coordinate corrections can theoretically provide centimetre scale accuracy for base machine positioning, stump and log positioning require additional knowledge of boom tip location and head orientation—factors that introduce further uncertainty. Understanding the performance of these systems is important when developing practical use cases.

In late 2025, the Wood Value Trial 2025 was conducted north of Uppsala, Sweden, with the aim to assess the performance of modern CTL harvesters across several key categories, including measurement precision (length and diameter), bucking performance, incidence of timber damage, and the capability and accuracy of stem and log positioning. Seven manufacturers participated in the trial, Log Max, Ponsse, Logset, John Deere, Ecolog, Rottne and Komatsu. All harvesters provided base machine positioning during felling, three included functionality for stump positioning, and one supported log-positioning. Stump positioning were evaluated by comparing recorded stump coordinates with control measurements collected using a handheld GNSS receiver with centimetre scale accuracy. The same comparison method was applied to evaluate log center positioning. For the stump positioning a sample of 30 stumps were evaluated for each manufacturer while the evaluation of the log positions consisted of 22 logs.

Results showed average stump positioning errors ranging from 0.16 to 1.38 m, with standard deviations between 0.11 and 0.73 m. For log positioning, the average error was 0.42 m, with standard deviations of 0.45 m and 0.26 m along the principal axes.

As a demonstration of a practical application using positioning, the Vinnova funded DigForeTrace and Mista Digital Forest projects used log positioning to enable identification of individual logs by forwarders, allowing stem specific information gathered by the harvester to be connected to individual logs carried out to roadside locations. As the identities of logs were known so too were the harvester measurements and combined with industry gate data, logs could be matched to a reasonable subset of candidates using length and diameter attributes. This passive tracing method produced lists of suggested matches for each log, recovering 67–76% of logs with an average of 3–33 suggestions per log. Because each candidate's unique harvester identifier is retained, the full suite of harvester recorded positioning data can be used to visualize where each log was cut and where each stem originally grew showcasing a use case for precise positioning information.

Keywords: Positioning; StanForD2010; Tracability; WoodValueTrial

Advanced Supply Chain Engineering to Support Fuel Treatment and Forest Restoration

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To mitigate wildfire risk in the western United States, forest fuel treatments such as mechanical thinning and prescribed burning have been widely implemented in fire-prone areas. While these treatments play a critical role in reducing wildfire hazards, they also present both opportunities and challenges. A substantial amount of biomass generated from fuel treatments offers new opportunities for bioenergy development. However, without effective downstream utilization, the resulting residues may lead to issues related to piling, transportation, and secondary combustion. Existing forest biomass supply chain studies have primarily focused on logging residues and sawmill residues, with limited attention paid to biomass derived from fuel treatments as a feedstock source. Moreover, spatially explicit assessments of biomass availability aligned with priority investment landscapes remain scarce. This study aims to develop a novel biomass supply chain framework that incorporates fuel treatment products into upstream biomass supply and to evaluate their supply potential and system costs under different utilization scenarios. The proposed framework integrates multiple methodological approaches, including forest management simulations based on the FVS-BioSum model, GIS-based spatial suitability analysis, and a comparative application of mathematical programming and machine learning techniques for supply chain optimization. The results are expected to provide quantitative decision support for the Wildfire Crisis Strategy and regional bioeconomy development. This study contributes to the coordinated advancement of sustainable forest management and the energy transition.

Keywords: Wildfire; Treatment; Biomass; Biochar

ERGONOMIC LAYOUT OPTIMIZATION OF MACHINERY USED IN FOREST PRODUCTS INDUSTRY: AN EXPERT-BASED MULTI-CRITERIA DECISION-MAKING APPROACH

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The layout configuration of machinery in forest products manufacturing facilities plays a critical role in occupational health and safety, operational efficiency, and production sustainability. In sawmills, timber processing plants, panel production units, and surface treatment lines, machine placement is generally designed according to production flow and space constraints. However, ergonomic risk factors such as awkward postures, repetitive movements, excessive material handling distances, limited visibility, noise exposure, and vibration are often insufficiently considered during layout planning. This may lead to work-related musculoskeletal disorders, increased accident risk, productivity losses, and long-term operational inefficiencies.

This study proposes an expert-based Multi-Criteria Decision-Making (MCDM) model to optimize ergonomic machine layout alternatives in forest products facilities. In the first phase, relevant ergonomic and operational criteria are identified through a comprehensive literature review and field observations. The proposed criteria framework includes: (i) operator reach distance, (ii) material handling and transportation distance, (iii) visibility and control field suitability, (iv) noise and vibration exposure level, (v) emergency accessibility, and (vi) maintenance accessibility. These criteria aim to integrate both safety-oriented and production-oriented considerations into a unified decision structure.

In the second phase, expert evaluations are collected from professionals in forestry engineering, occupational health and safety, production management, and ergonomics (minimum 10-15 experts). Criteria weights are determined using either subjective approaches such as AHP or Fuzzy AHP, or objective weighting techniques such as Entropy or CRITIC, allowing a comparative assessment of weighting strategies. Subsequently, alternative layout scenarios such as linear flow layout, U-shaped layout, and cellular layout are developed for a representative forest products production system. These alternatives are ranked using TOPSIS or Fuzzy TOPSIS to determine the most ergonomically and operationally suitable configuration.

The proposed model provides a structured decision-support framework that simultaneously minimizes ergonomic risk and supports operational efficiency. A sensitivity analysis is conducted to evaluate the robustness of ranking results against changes in criteria weights.

Unlike conventional forestry mechanization studies that primarily focus on productivity and machine performance, this research integrates ergonomic risk assessment and occupational safety into layout optimization. The findings contribute to the development of sustainable and human-centered mechanization strategies in forest products manufacturing. The proposed approach is practical, adaptable to different facility types, and aligned with the objectives of the FORMEC symposium in promoting advanced and responsible forest mechanization solutions.

Keywords: Ergonomics; Machinery; MCDM; Risk

DEVELOPING THE FUTURE ASSISTANT SYSTEMS FOR HARVESTER OPERATORS

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The use of the cut-to-length method as a wood harvesting system creates a demanding operating environment for harvester operators, especially in the Nordics. In addition to the harvesting method itself, high productivity demands and environmental conditions such as terrain, weather, vibration and cabin tilting increase the demands of the operator's work. This environment places mental, physical, and cognitive strain on the operator, making the work holistically challenging. The workload of harvester operators can be reduced through various operator assistance systems. Currently, harvesters are already equipped with some assistance systems such as boom-tip control, automated bucking system, a reversing camera, and GPS positioning and maps. These systems support the operator's decision-making and machine control. In the future, operator assistance systems will increasingly utilize forest machine data produced by various sensors, reducing unnecessary tasks and workload for the operator.

The objectives of this study were to determine what kinds of operator assistance systems will be needed in the future, how information provided by these systems should be presented, and what types of support operators require in their work. In addition, the study examined which assistance systems and advance information harvester operators currently use and how they receive feedback on their work. The interviews included 50 harvester operators across Finland and were semi-structured, incorporating a two-step Likert scale, with additional open-ended questions added to complement and deepen the information obtained from the Likert-scale items. The two-step Likert scale was adapted from the Importance–Performance Analysis approach and analysed within this framework, enabling a combined assessment of how important each factor is to operators and how well it currently performs.

According to the results, harvester operators wish for assistance systems to support controlling thinning intensity, reporting harvest quality, and identifying tree characteristics and quality. These systems rely on data collected by mobile LiDAR scanners, which capture precise 3D measurements of the forest stand and make it possible to automatically identify tree attributes relevant to thinning and quality assessment. Operators were generally satisfied with the current method of presenting information on a traditional computer display, but they also expressed interest in new presentation methods such as AR-glasses and head-up display (HUD) systems. Among the existing assistance systems, GPS positioning and maps were considered the most essential. Boom-tip control was also regarded as useful, although operators felt that the system still requires further development. Receiving advance information about legally protected forest nature sites, buffer zones around water systems, and roadside landing areas was considered particularly important. In addition, based on the interviews, operators expressed a desire to receive regular monthly feedback on their work.

This study provides new, up-to-date insights into the needs of harvester operators regarding the development of operator assistance systems, thereby supporting the future development of forest machines in collaboration with manufacturers, contractors, operators, and researchers.

Keywords: harvester; CTL; decision-support; ergonomics

Predicting gravel road bearing capacity based on weather data and calibration visits

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Information about the trafficability of gravel roads is of paramount importance for sustainable, cost-effective, and year-round delivery of timber for industrial use. For heavy vehicles like a timber truck, it is essential that the roads are in a trafficable condition when they are being driven on. The trafficability of forest roads varies depending on the season and weather conditions. Many roads become impassable during the spring thaw and following torrential rain. However, there are no models which could predict the bearing capacity of gravel roads in real-time and for the near future, i.e., the next few days.

The aim of this study was to develop and evaluate a simple dynamic bearing capacity model for gravel roads based on weather and soil type data, i.e., inputs which are readily widely available, and thus could be easily upscaled to encompass eventually a whole country. A further aim was to test the sufficiency of weather and soil type data and to evaluate the potential of calibration measurements of roads to improve the predictions.

The road data consisted of ten approximately 100-m long gravel road segments in eastern Finland. The road segments represented typical forest road conditions regarding subsoils and road structures. Data on air temperature and rainfall were recorded by nearby weather stations on hourly basis. Furthermore, bearing capacities of the road segments were sampled using a light-weight deflectometer at 20 m intervals during the 2.5-year data collection period.

The role of temperature, rainfall, soil type, and their interactions were investigated using a linear mixed-effects model. For temperature, we used a 72-hour moving average capped at the freezing point. For rainfall, we used a 48-hour moving average. The optimal number of calibration visits was estimated using a cross-validation approach in which the model was tested using one segment at a time and trained using the other nine segments.

Rainfall, temperature, and soil type alone explained about 19% of the total variance based on the linear mixed effects model. When road segment and specific location are also included, the full model can explain 48% of the variance in bearing capacity. In general, the predicted dynamical behaviour followed the trend of the bearing capacity measurements for all road segments. However, the predictions tend to have less variation than the ground measurements, especially the minima and maxima tend to be over- and underpredicted, respectively. Two calibration measurements improved the prediction accuracy by approximately 15%. After two field visits the benefit of additional visits was marginal.

The relatively simple prediction model can be further improved with additional explanatory variables, such as features extracted from LiDAR data. The calibration is independent from the used prediction model, and the field visit can be done any time. However, to get unbiased estimates when the bearing capacity is at its lowest, more measurements are needed in poor conditions.

Keywords: "Trafficability; Forest road; Logistics"

A Systems Dynamics Framework for Analysing Forest-to-Value Chains: A Conceptual Approach with Application to Harvesting and Transport Operations

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Maintaining the competitiveness of the forest sector requires a holistic understanding of interactions across the forest-to-value chain, particularly within harvesting and transport operations where inefficiencies can propagate system-wide effects. This work presents a conceptual framework based on systems dynamics and systems-based thinking to investigate structural behaviour, feedback mechanisms, and bottlenecks in forest value chains. The approach integrates causal loop diagrams, stock-and-flow modelling, and scenario simulation to represent nonlinear relationships among forest resources, harvesting capacity, logistics performance, operational costs, and supply reliability.

The proposed framework is designed to be combined with artificial intelligence and optimization methods, enabling data-driven parameterization, predictive analysis, and evaluation of alternative decision strategies. Machine learning techniques support estimation of uncertain variables and forecasting of system responses, while optimization models assess harvesting allocation, fleet deployment, and transport planning under operational constraints.

Preliminary results from case studies in Australia illustrate the applicability of the framework and demonstrate its potential to identify leverage points, inefficiencies, and unintended consequences within forest operations. These early findings highlight how integrated systems modelling can provide insights not captured through conventional analytical approaches. The study positions the framework as a decision-support tool to assist industry stakeholders in diagnosing system limitations and designing interventions that improve productivity, resilience, and long-term competitiveness across the forest sector.

Keywords: Systems dynamics; value chains

Improvements to a Medium-Sized Drum-Type Chipper for Adaptation to Gasification CHP

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In Japan, woody biomass power generation is increasing due to the Feed-in Tariff (FIT) scheme. However, woody biomass power generation suffers from low energy efficiency. Therefore, improving energy efficiency through combined heat and power (CHP) generation is being considered. Preferential treatment under the FIT program for small-scale facilities (generating less than 2 MW) has begun, and the introduction of gasification CHP systems, suitable for small-scale applications, is advancing. However, gasification imposes stringent requirements on fuel, leading to difficulties in procuring it and soaring fuel prices that cause business failures. Fuel chips for gasification require minimal fines and a uniform, relatively larger particle size. Large chippers designed for paper mill chips can produce a large proportion of relatively large chips. However, not only do these chips fuel applications compete with paper applications, but the production scale also far exceeds the demand of small-scale gasification CHP plants, leading to price increases. Conversely, medium- and small-sized chippers, which produce quantities suitable for small-scale gasification CHP, tend to generate more fine particles and struggle to produce relatively large chips. This fact necessitates screening to select chips suitable for fuel production, further contributing to fuel price increases. Therefore, a medium-sized drum-type chipper was modified to produce chips suitable for gasification CHP. Preliminary test results showed that chips produced by a commercially available medium-sized drum-type chipper met the ISO P31s specification. However, compared with the chip requirements specified by various gasification CHP boiler manufacturers, the chips contained too much fine material and lacked sufficient larger chips. We therefore conducted development and testing to reduce fine material and enable the production of larger chips. To reduce fine particles, the number of blades was reduced from 6 to 3. To produce larger-sized chips, the rotor speed and feed rate were optimized. Using a chipper equipped with a standard drum and a chipper equipped with a prototype drum featuring 3 blades, and two types of screens, we conducted chipping operations on sets of 10 Japanese red pine logs with a butt diameter of less than 30 cm and a length of 2 m. We observed the operations and collected samples of the produced chips. Each condition was tested three times. After returning to the laboratory, the samples were dried in the oven, weighed to determine water content, and then sieved. The particle size analysis showed that reducing the number of blades significantly decreased fine particles and increased the proportion of larger chips; however, this still fell slightly short of the gasification CHP boiler manufacturers' requirements.

Keywords: blades; rotor; feeder; size

Task- and Load-Dependent Effects of Passive Exoskeletons in Simulated Manual Handling: A Laboratory Study Using 3D Kinematics and Ergonomic Risk Evaluation

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Manual handling in forestry and nursery work involves repetitive low postures, trunk bending, and short-distance load carriage, all of which can elevate the risk of musculoskeletal disorders (MSDs). Passive exoskeletons are sometimes suggested as a practical way to reduce postural exposure and strain, but their effectiveness varies depending on the job. Their effectiveness depends heavily on the activity required movements (i.e., the task pattern) and the weight of the load being handled.

So far, either the kinematics of movement or the ergonomic risks associated with work performance and specific tasks are examined. In this laboratory study, we compared the two methods simultaneously by quantifying the influence of different passive exoskeleton models on kinematic exposure metrics and ergonomic risk indicators during two simulated manual task sets.

The first, Task Set A, simulated tree planting and included low-load repetitive handling, repeated trunk flexion and kneeling, as well as upright walking over 20 meters while placing small items (0.5 kg every 2 meters; 1 kg every 4 meters). Task Set B (Moderate-Load Handling and Carriage) simulated plant seeding and included repeated lifting of loads with deep squatting, short-distance walking, and lifting/carrying loads of 5, 10, and 15 kg over 4 meters.

Participants performed the protocol both with and without an exoskeleton (two models for Task Set A and three models for Task Set B). Whole-body motion was digitally recorded at 60 Hz samples using Inertial Movement Units-based motion capture and converted into 3D ergonomic joint angles and movement acceleration.

To provide a comparable assessment, we analyzed several kinematic exposure outcomes, including: (i) time spent in trunk flexion/extension, (ii) trunk flexion/extension dose (time × depth in degrees), (iii) relative flexion/extension between lower extremity segments and pelvis, (iv) upper arm positions and flexion/extension dose, and (v) trunk sway, pelvis movement, and knee position as a stability-related proxy during walking/carrying. We contextualized kinematic exposures using ergonomic risk evaluation frameworks, including ISO 11226 (angle–time postural loading) and EN 1005-4 (repetition characteristics). We complemented these with time-based distributions consistent with OWAS/RULA logic for identifying high-risk postures. Condition effects were summarized as within-participant differences versus the no-exoskeleton condition, with confidence intervals.

The results show that the effects of passive exoskeletons vary across the equipment × task combinations. In the low-load pattern, which is dominated by bending and kneeling, the main potential benefits are reducing the movement dose and improving walking and activity stability. These are closely related to body strain and performance in repetitive tree nursery activities. In the moderate-load pattern, 'effectiveness' is better judged by whether the exoskeleton allows efficient squatting and stable carrying without increasing demands for upper-arm elevation or trunk sway/rotation, rather than by reducing trunk bending alone. In practice, these findings support the selection of exoskeleton models based on dominant task patterns and expected load ranges. They also emphasize the need for field testing on uneven terrain and with full protective equipment and working tools before operational implementation.

Keywords: Exoskeletons; Movement&Kinematics; Ergonomics; Health&Safety

Presentation of a meta-analysis of the current state of lifting force measurement in tree felling with chainsaws

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Working conditions in forests are changing mainly due to the current state of forests as a result of climate change. More deadwood and pre-damaged wood are being felled, and there is more deadwood, especially in the crowns of the deciduous trees to be felled. As the risk increases, so does the potential danger of accidents. The results of the KWF accident statistics (<https://unfallzahlen.kwf-online.de>) show that there is an increased risk of accidents when felling trees manually with a chainsaw within a 5 m radius of the tree. For this reason, mechanical felling wedges are required to fell the tree manually from a safe distance with reduced risk.

The KWF e.V. is aware of the current state of knowledge in this area through previous research work and exchanges with partners in the field.

A basic data analysis was carried out as part of a bachelor's and master's thesis by Mark-Fabian Franz in 2020 and 2023. The topics covered were the required lifting forces and distances for different tree lean angles and for different hinge (height and width). One result was the creation and development of an online calculator to determine the required lifting force for a hanging tree. (<https://hubkraftkalkulator.kwf-online.de/>)

Furthermore, findings on the changing lifting forces and distances with changing dimensions of the hinge (height and width) were recorded.

The resulting knowledge about the interactions between tree species and tree condition as well as lifting force and distance can be used to optimize the selection of tools, reduce misjudgments and thus significantly increase occupational safety.

The development and application of the measurement methodology for lifting force measurement also took place in this work. Current literature on further studies reviewed and analyzed within this work. Furthermore, practical partners, manufacturer contacts and interviews with practical partners as well as literature from past decades are available to take into account the development of break bar geometries.

However, further necessary measurements and comparisons with practice are still lacking. The determination of lifting force has been published internationally on several occasions. It is necessary to investigate which measurement methods were used in each case. Furthermore, the differences between the various measurement methods used in terms of results should be explained.

A meta-analysis is currently being prepared on this topic in order to compare the measurements taken. The research question is: 'How can the current state of knowledge about lifting forces and distances be further developed and the measurement methods improved?'

Another point is the consideration of the lifting force required for tree felling with a lifting cylinder compared to the lifting force required for tree felling using a technical felling wedge. The hypothesis here is that there is a slight difference in the lifting force required for tree felling using a lifting cylinder compared to that required using a felling wedge. However, this will be irrelevant in practice due to the necessary safety margin.

Keywords: Chainsaw-Work; Tree-Felling; Lifting-Forces; Wedges

Enhancing the reliability of logging residue forecasts through operator insights and cross-sector collaboration

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Growing interest in logging residues in Sweden, resulting from geopolitical developments and ambitions for energy independence, has intensified the need for precision planning of wood fuel supply. More than 15 years ago, Skogforsk developed a system that uses harvester production files to forecast volume and location of logging residues at stand level. Implemented through the calculation module “hprCM”, the system is used by several forest companies. Accurate forecasts require that harvester operators correctly distinguish fuel-adapted areas from non-adapted areas. In practice, harvester and forwarders frequently use logging residues to reinforce strip roads and wet areas to prevent soil damage, and such adjustments must be manually registered via the keyboard or touchscreen in the onboard computer.

As part of the Swedish Energy Agency-funded project “Improved forecasts of logging residues for precision planning”, we performed a large-scale evaluation of the forecasting system. The analysis revealed substantial variability in how contractors used the system and how well the forecasted volumes matched the measured volumes at the heating plants. To better understand the underlying causes, semi-structured interviews were conducted with six experienced harvester operators. The interviews focused on planning, instructions, working methods, system use, and feedback routines connected to logging residues. The results identified several categories of usability issues related to system functionality, instructions, follow-up procedures, and attitudes toward logging residues.

Based on these findings, Skogforsk proposed a set of potential solutions and subsequently organized a workshop to anchor ideas and discuss the proposed measures. The workshop brought together representatives from forestry and energy companies, IT developers, and machine manufacturers, which together identified concrete, implementable solutions which aim to increase the accuracy of precision planning of wood fuel supply. A new follow-up assessed the progress of implementation, highlighting pathways to improve short-term forecast accuracy and long-term processes for working with logging residues.

Keywords: operator-behavior; usability; precision-planning; HCI

Physiological Workload and Noise Exposure During Semi Mechanized Forest Road Maintenance

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To ensure the continued functionality and intended purpose of forest road infrastructure, regular maintenance interventions are required. Maintenance operations employ technologies with differing levels of mechanization, which subsequently influence task difficulty and workers' exposure to occupational noise. The study examined a technological system representative of practices in small private forestry enterprises in Slovenia, comprising three machines: a tractor (FENDT Farmer 309 LS Turbomatik) equipped with boom-mounted trimmer and grading attachment (KAHLBACHER), a truck (MAN 414 F2000), and a roller (BOMAG BW-120 AD-4).

Measurements of heart rate and noise exposure were performed over a total of 4.8 hours on three workers across individual maintenance phases. The results indicated that the physiological workload—measured as the percentage of Heart Rate Reserve (HRR)—reached 33.6% during non-productive time, which is 8% higher than during productive tasks. Within productive phases, the highest HRR value occurred during manual road cleaning following trimming (56.8%), whereas the lowest was recorded during grading (19.6%). Noise exposure (LAeq) during non-productive periods was 81.9 dB(A), exceeding productive-time exposure by 3.2 dB(A). Among productive tasks, the highest noise level was recorded during rolling with a roller without a protective cabin (88.4 dB(A)), and the lowest during manual road cleaning (70.5 dB(A)).

The findings suggest that, when considered as an integrated process, forest road maintenance does not exceed established thresholds for physiological workload and occupational noise exposure (HRR = 40%; lower exposure limit for LAeq = 80 dB(A)). However, these limits are exceeded at certain workstations and during specific operational phases, necessitating the implementation of preventive measures to mitigate overexertion and overexposure. The study further indicates that with increasing levels of mechanization, excessive workloads tend to shift from productive to non-productive periods, highlighting the need for active monitoring and management of activities conducted during non-productive time.

Keywords: Ergonomics; Road; Maintenance; Mechanization

Poster Presentations

Productivity, cost and energy efficiency in the recultivation of short rotation poplar plantations

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Recultivation is an essential task in the management of Short Rotation Forestry (SRF) poplar, which is grown on arable land and is generally integrated within a crop rotation system. This task involves destroying the poplar stumps and tilling the soil down to a depth that is suitable for establishing a new farm crop. Recultivation can be performed using versatile heavy forestry mulchers that simultaneously mulch the soil and remove stumps. The objective of this study was to develop long-term benchmark performance metrics for industrial mulchers used in the recultivation of SRF poplar. The study involved the collection of long-term data on a forestry mulcher working on 486 ha of harvested SRF poplar stands. Data were collected across 18 sites in Germany and Slovakia by maintaining detailed, site-specific logs for two years. Data recorded included position, time use, and fuel consumption, number of teeth replaced, soil type, and resprouting class. The data were analyzed using bootstrapping, allowing robust calculation of means, confidence intervals and regression models despite the low number of sites and non-normal data. The results show that mean fuel, time and teeth consumption were respectively 181 L ha⁻¹, 3.26 h ha⁻¹, 7.47 teeth 10xha⁻¹. The number of passes and soil type significantly affected fuel consumption, time consumption, and tooth wear. In contrast, resprouting and field size did not significantly affect the same dependent variables. The study's findings provide key benchmark figures for planning and estimating the cost of SRF poplar recultivation

Keywords: plantation; SRF; termination; fuel

Exploring mechanized harvesting systems for continuous cover forestry in the Nordics

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Interest in continuous cover forestry (CCF) is increasing across the Nordic countries, driven by forest owner preferences, certification requirements, and policy developments. Compared with rotation forest management, CCF typically results in lower harvested volumes per hectare (m³/ha) and smaller total removals per tract (m³/tract). Combined with a long-term trend towards smaller tract sizes, these conditions challenge the cost-efficiency of the conventional Nordic cut-to-length harvesting system comprising a harvester and a forwarder (two-machine system; TMS). In particular, fixed costs such as machine relocation are spread over smaller volumes, increasing harvesting costs per cubic metre.

We examine the potential of single-machine systems (SMS) to improve cost-efficiency and maintain a high level of mechanization under Nordic CCF conditions. SMS perform cutting and extraction with a single machine, thereby incurring only one machine relocation cost per tract instead of two. As a result, the relative competitiveness of SMS increases as tract size, harvested volume per hectare, and extraction distance decrease – conditions that are becoming increasingly common with the expansion of CCF and forest road networks in the Nordics.

SMS are commonly categorized as either harwarders or dual machines. However, the only commercially available SMS in the Nordics today are small-sized dual machines (SmallSMS) designed for harvesting small-diameter trees. These machines cannot fell and process large trees, which is a drawback because CCF harvesting often involves thinning from above and cutting large trees (>1 m³ per stem). Consequently, current SmallSMS are poorly suited for widespread application in Nordic boreal CCF stands.

Therefore, we explore the need for large single-machine systems (LargeSMS) capable of handling large trees while minimizing damage to the remaining stand. By combining lower relocation costs with sufficient harvesting capacity, LargeSMS have the potential to outperform TMS on low-removal tracts, improve machine utilization, and reduce total harvesting costs. Maintaining mechanized harvesting under these conditions is also important from a safety perspective because in the Nordics, motor-manual harvesting is largely unacceptable due to substantially high accident and fatality rates.

Using key productivity- and costing factors including removal per hectare, tract size, assortments' volume distributions, extraction distance, and relocation costs, we simulate TMS and LargeSMS concepts (harwarders, dual machines, etc.) across a range of realistic Nordic CCF conditions. The results will identify economic and operational break-even points at which LargeSMS are more competitive alternatives in CCF than TMS. Given that CCF continues to expand in Nordic forestry, the economic disadvantages of TMS on low-removal tracts are most likely to become more pronounced. At the same time, growing adoption of CCF suggests that market conditions may now support renewed development and commercialization of LargeSMS. Therefore, we postulate that LargeSMS represent a promising pathway towards cost-efficient and safe harvesting in Nordic CCF.

Keywords: logging; harwarder; dual machine

Precision volume estimation of teak stems: validating AdQSM algorithm and field-derived measurements

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Accurate stem volume estimation is critical for forest inventory and timber value assessment. While traditional field measurements combined with wood density analysis provide reliable data, they are often destructive and time-consuming. Terrestrial Laser Scanning (TLS) offers a high-resolution, non-destructive alternative through advanced algorithms like AdQSM. This study aims to validate the accuracy of the AdQSM algorithm in estimating the stem volume of Teak (*Tectona grandis* Linn.) by comparing it with field-derived volume measurements. Data were collected from 30 sample teak trees. The reference "field volume" was determined by weighing the actual stems and converting the mass to volume (m³) using precisely measured wood density. Simultaneously, TLS was used to capture 3D point clouds of the same 30 trees, which were processed using the AdQSM algorithm to calculate the stem volume by excluding branches and foliage. The comparative analysis showed a high correlation between the AdQSM-derived volumes and the field-measured volumes. The AdQSM algorithm demonstrated high precision with a coefficient of determination (R²) of 0.9562 and a low Root Mean Square Error (RMSE). Statistical analysis indicated that the volumes estimated via AdQSM did not differ significantly from the field-derived values. The AdQSM algorithm proved to be a highly reliable tool for non-destructive stem volume estimation in teak plantations. By providing results comparable to intensive field measurements, this technology enables rapid, high-accuracy forest inventories and supports sustainable forest management practices.

Keywords: Teak; Lidar; Stem Volume

ForestIN (Forest INventory): A smartphone application for structured forest inventory data collection

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Forest inventory data collection in operational forestry remains largely dependent on manual measurements recorded on paper forms or fragmented digital tools. Such practices increase the risk of transcription errors, compromise traceability between plots and trees, and generate delays between field acquisition and subsequent analysis. In remote forest environments, limited network connectivity further constrains the use of conventional digital platforms, often forcing practitioners to rely on disconnected workflows and post-field data consolidation. These limitations reduce operational efficiency and introduce inconsistencies that may propagate through downstream analyses and management decisions. As forest management increasingly demands transparent, standardised, and precision-oriented information, there is a clear need for digital systems capable of structuring field data capture while remaining functional under real operational constraints.

To address these challenges, this study presents ForestIN, a mobile and web-based application designed to digitise forest inventory data within a unified relational workflow. Developed using the Google AppSheet no-code platform and deployed across Android, iOS, and web interfaces, the system enables flexible implementation without requiring advanced programming expertise. ForestIN is structured around a relational database linking inventory plots, individual trees, and species records through universally unique identifiers, ensuring logical consistency and full data traceability. The application supports georeferenced measurements, multimedia documentation, and offline data capture with deferred synchronisation, allowing uninterrupted operation in areas without network coverage. The system was tested using forest inventory datasets from Spain and Finland to evaluate structural robustness and transferability across different operational contexts. Results demonstrate reliable offline performance, preservation of relational integrity during synchronisation, and export of complete datasets in interoperable formats. By integrating traditional field measurements into a scalable digital framework, ForestIN enhances data reliability, operational continuity, and collaborative forest management practices.

Keywords: Forest_inventory; Precision_forestry; App; Google_AppSheet

Development of a Real-Time Wheel Rut Monitoring System for Forwarders: First Results

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Forest operations with forwarders frequently cause soil deformation and wheel rut formation, negatively affecting soil bearing capacity, hydrological processes, and longterm forest productivity. Existing studies primarily focus on post-operational rut assessment using UAV photogrammetry, LiDAR-derived digital terrain models, and machine learning-based image segmentation, as well as predictive modelling based on soil moisture, traffic intensity, and machine load. However, these approaches are predominantly retrospective and do not support real-time operational decision-making during timber extraction.

This study proposes the development and validation of an integrated real-time wheel rut monitoring system embedded in a forwarder. The system combines distance sensors, GNSS positioning, and LiDAR technology to continuously detect and quantify rut depth and spatial distribution during machine operation. The collected data enable dynamic assessment of soil impact and provide immediate feedback to operators, supporting adaptive driving strategies and optimized extraction routing.

The expected outcomes include a functional prototype of the monitoring system, methodological evaluation of measurement accuracy and reliability, and practical recommendations for its implementation in forest operations. By enabling objective, data-driven soil impact assessment in real time, the proposed solution contributes to sustainable forest management and advances the integration of smart technologies within the bioeconomy sector.

Keywords: Wheel rutting; Real-time monitoring

Integrating Harvester Production Data and Remote Sensing for Root Rot Risk Assessment

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An integrated harvesting site monitoring methodology was developed to support data-driven forest management and root rot risk assessment by combining operational harvester data, field measurements, and spatial analysis. The study aimed to evaluate whether terrain and multispectral predictors can reliably distinguish healthy from root rot-damaged stands at the sample plot level.

Root rot occurrence was identified using harvester production report (HPR) data and validated through field measurements in 905 sample plots. Harvested stumps were classified as healthy or root rot-damaged, and plot-level predictors were derived from a 5 m resolution digital elevation model and multi-season Sentinel-2 imagery (2021, pre-harvest conditions). In total, 42 terrain and spectral variables were extracted and used in a structured machine learning workflow.

The dataset was balanced using upsampling and divided into training (80%) and testing (20%) subsets. An XGBoost classification model was trained using 5-fold cross-validation with grid search optimization based on AUC. Model performance was evaluated using accuracy, balanced accuracy, sensitivity, specificity, F1 score, and Cohen's Kappa.

The model achieved total and balanced accuracy of 74.4%, with moderate agreement ($\kappa = 0.49$). Sensitivity (71.1%) and specificity (77.7%) indicate reliable discrimination between healthy and damaged plots. The most influential predictors were the normalized height model and depth-to-water index. Healthy plots were located on slightly higher microsites, while damaged plots were associated with marginally lower depth-to-water values.

The results demonstrate the potential of integrating harvester data and remote sensing predictors for spatially explicit root rot risk assessment and provide a foundation for developing digital forestry decision-support tools.

Keywords: harvester, StanfordConvertXML, root rot

Ergonomic Assessment of an Ecotrac Cable Skidders

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Skidders used in forest operations are regarded as specialized machines optimized for effective and safe wood skidding across rugged terrain. Their dimensions, design, and various technical attributes are primarily influenced by practical considerations, such as productivity, durability, energy efficiency, environmental sustainability, and immediate worker safety. However, there is limited knowledge about the ergonomics of these machines, as negative ergonomic aspects often accumulate over time and become apparent much later than more immediate features. Featured studies imply ergonomic inferiority of skidders in comparison to other extraction machinery. The aim of this study was to conduct a comprehensive assessment of the ergonomic features of skidders manufactured by Croatian company Hittner Ltd, and to propose possible solutions for their improvement. For this task, ergonomic guidelines (checklist) for forest machines, established by several European countries, were used. Skidders Ecotrac 60V and 140V were assessed at the Hittner Ltd. facility. Results show significant drawbacks in Cab access, Working posture, and Winch sections. Workstation levelling, better seat, thicker steel rope, and a hydraulic spool-out device were offered as a major potential means of improving the ergonomic profile.

Keywords: forestryergonomics; ergonomicprofile; skidder; ergonomicguidelines

Field Validation of a Mobile Multi-Sensor LiDAR System for Dynamic Forest Road Damage Detection

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Reliable forest road condition monitoring is essential for safe and cost-efficient timber transport. Conventional visual inspections are labour-intensive and often fail to provide objective, repeatable data for maintenance planning. This study presents the development and field validation of a vehicle-mounted multi-sensor LiDAR system for automated forest road damage detection under operational driving conditions.

The system integrates 16 single-beam LiDAR sensors with a central controller that continuously measures road surface deviations and records georeferenced damage events when calibrated thresholds are exceeded. A minimum vehicle speed limit (1 m s^{-1}) prevents duplicate detections. The system is designed for installation on transport vehicles, enabling routine road condition monitoring without additional inspection costs.

Field trials were conducted on a 2.3 km forest road section at speeds from 10 to 80 km h^{-1} , reflecting typical timber transport conditions. Manual GNSS-based surveys of potholes $\geq 5 \text{ cm}$ depth were used for validation. Spatial agreement between manual and automated detections was assessed using the Jaccard index at tolerance distances of 2, 3 and 5 m.

From 260 manually recorded potholes and 211 automated detections, agreement increased with tolerance distance: 0.53 (2 m), 0.64 (3 m), and 0.73 (5 m). Results indicate reliable detection performance when accounting for GNSS uncertainty. Higher driving speeds reduced precise localisation of individual defects but allowed identification of damaged road segments relevant for maintenance prioritisation.

The system supports scalable, data-driven forest road management, improves transport safety, and provides a practical tool for integrating digital road quality monitoring into forest logistics operations.

Keywords: LiDAR; Automation; Infrastructure; Monitoring

A Multidisciplinary Assessment of Slope, Surface Roughness and Vibrations in Evaluating Forest Trail Inclusivity: Presentation of the Methodology

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The FORS4Wheels is a Croatian Science Foundation project that is focused on the experimental and quantitative analysis of the accessibility of forest and urban green trails for wheelchair users, to determine the relationship between the morphological characteristics of trails and the biomechanical as well as subjective load experienced by users. The study integrates geodetic, engineering, biomechanical, and ergonomic methods to ensure an objective and multi-level assessment of accessibility.

Longitudinal trail profiles were measured using a high-precision GNSS RTK system connected to the national reference positioning system to achieve centimeter-level accuracy in both horizontal and vertical components. In areas with reduced satellite signal availability, a total station was used to ensure data consistency and reliability. Based on the collected coordinates, detailed longitudinal profiles were generated, and the trails were segmented according to slope categories and the length of slope sections within a GIS environment.

Surface roughness was quantified using a high-precision laser scanner to capture the longitudinal microprofile of trail surfaces. The acquired data were processed using specialized software, and roughness was expressed through the International Roughness Index (IRI) as a standardized indicator of longitudinal unevenness. This approach enabled objective comparison of different surface materials and the quantification of micro-irregularities relevant to wheelchair mobility.

Vibration exposure during movement was measured by mounting tri-axial accelerometers on the wheelchair frame. The sensors recorded accelerations in the vertical, longitudinal, and lateral directions, and analyses included maximum amplitudes, root mean square (RMS) values, and the frequency spectrum of vibrations. The data were processed in numerical analytical environments, and the results were correlated with measured slope values and IRI indices to determine the relationship between geometric and surface parameters of trails and the vibration load experienced by users.

Physiological load was assessed through continuous heart rate monitoring while participants traversed defined trail segments. The relative increase in heart rate was used as an indicator of physical exertion intensity. At the same time, subjective workload was evaluated using an adapted questionnaire based on the NASA-TLX methodology, assessing physical demand, perceived safety, level of frustration, and perceived control of movement.

By integrating spatial, surface, vibration, physiological, and perceptual data, a multidisciplinary analytical framework was developed for assessing forest trail inclusivity. The results will enable the identification of critical slope and roughness thresholds associated with increased vibration exposure and subjective feelings of insecurity. This methodology provides a scientifically grounded basis for defining technical guidelines and threshold parameters in the planning and adaptation of forest trails, with the goal of ensuring safe and independent mobility for wheelchair users.

Keywords: Accessibility; Roughness(IRI); Vibration; Wheelchair

Resilience of Selected European Forest Value Chains: social-ecological challenges and implications for forest bioeconomy

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This research investigated the resilience of European forest value chains (FVCs) under increasing climate, market, and operation-related disturbances, focusing on how innovation and management practices enable adaptive and sustainable forestry systems. Resilience was defined as the capacity of FVCs to absorb shocks, adapt operations, and maintain core production and ecosystem functions.

A mixed-methods approach combined bibliometric and qualitative analyses of forest bioeconomy innovation with quantitative assessments using an Operational Resilience Framework across five European case studies (Czech Republic, Croatia, Germany, Finland, and Spain). A complementary local-level economic analysis examined operational and market drivers of resilience, supported by stakeholder perspectives.

Results indicate that while technological and mechanisation-based innovations improve short-term system stability, long-term resilience depends on proactive management, diversified processing and logistics capacity, coordinated actor networks, and ecosystem-based strategies. The findings highlight the need to integrate technological solutions with adaptive governance and system-level innovation to strengthen resilient forest value chains, supporting a sustainable forest-based bioeconomy transition relevant to FORMEC 2026 in Prague.

Keywords: Salvage logging, innovation, technologies

Analysis of work efficiency and factors affecting the time required for stump grinding using a Bandit model 2550 machine

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Stump grinders have long been used to remove stumps after trees have been felled. These machines are particularly useful in hard-to-reach areas, such as urban areas, where it is important to remove the stump quickly without damaging the immediate surroundings. When using stump grinders, it is important to correctly determine the efficiency of this process due to the high labor costs. The efficiency of stump grinding can be presented in various ways. In forest areas, grinding efficiency is defined as the number of stumps ground per area (stumps · ha⁻¹) or the number of stumps ground per hour (stumps · h⁻¹). The term “area milling efficiency” (ha · h⁻¹) with stumps per hour is also used, which is widely used, for example, in the case of milling areas after fast-growing plants. For urban areas, efficiency is usually defined as the number of stumps per working day (stumps · day⁻¹). In this case, the milling capacity is influenced by many factors related to the fact that stump milling in cities is technically and organizationally complex, which is related to the specific nature of the workplace and the limited number of machines that perform this work. It is also important to note that during stump grinding, soil is ground along with the wood, which complicates the analysis when determining productivity. There is little information in the literature on the analysis of the productivity of stump grinders operating in cities. This paper presents an analysis of the productivity of stump grinders operating in the city. The paper presents an analysis of the performance of the Bandit Industries, Inc. model 2550 stump grinder, based on a 3-day chronometer study of the machine's operation while grinding 23 tree stumps in Krakow, a large city in Poland. An analysis of the main factors affecting the time and efficiency of grinding was also performed, taking into account, among other things, the volume of the ground cavity, stump parameters, wood species, and soil moisture. The relationship between work efficiency and the root content in the ground mass was determined. As shown, the operational efficiency of the grinder was 2.88 m³/h, while on a working day it was low at 0.73 m³/h, which was directly related to the activities necessary to perform grinding in the city.

Keywords: stump grinding, work efficiency,

Estimating the availability of unused dead wood materials introducing Japanese forestry machinery in Mongolia

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Mongolian forests have accumulated large quantities of deadwood due to forest aging and limited utilization. While in Europe the retention of deadwood is often considered to enhance biodiversity, in Mongolia it is increasingly regarded as a driver of forest degradation, contributing to wildfire risk, insect outbreaks, and declining forest health. Consequently, active removal and utilization of deadwood is being promoted. Building on the assessment by Ikeda et al. (2022), which estimated the national stock of unutilized deadwood in Mongolia, this study evaluates the potential for deadwood utilization through the introduction of Japanese forestry machinery. Specifically, the accessible volume of deadwood under mechanized operations was compared with that obtainable using conventional Mongolian skidding methods (human-powered, horse-powered, tractor skidding).

The analysis covered 96,379 subgroups, representing an estimated 94,067,412 m³ of deadwood. Japanese forestry machinery showed feasibility in 37,048 subgroups, equaling 1,131,751 ha with a total estimated volume of 35.7 million m³. The estimated logging cost using Japanese machinery, which included stumpage, layout, felling, primary and secondary transportation, was 113,126 MNT/m³. In contrast, traditional skidding methods yielded lower costs of 68,590 MNT/m³. As a result, 38% of the analyzed area could be profitably harvested using Japanese equipment, compared to 68% using traditional methods. Transport efficiency was constrained by an assumed truck speed of 5 km/h due to off-road conditions. However, road improvements could substantially increase transport efficiency, enhancing the economic feasibility of mechanized utilization.

This study highlights the trade-offs between modern machinery and traditional methods in Mongolia. While mechanized harvesting enables the recovery of large volumes of deadwood, traditional methods currently provide lower costs and wider applicability. Both approaches may play complementary roles in deadwood utilization, contributing to forest restoration and renewable biomass supply. Future research will integrate road attributes and vehicle specifications into transport cost modeling to refine utilization estimates and identify optimal strategies.

Keywords: Feasibility; Off-road; Skidding; Transportation;

AR Head-Up Display with LiDAR for Real-Time Assistance in CTL Harvester Machine

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This study examines a real-time assistance concept designed to enhance operator decision-making and cognitive ergonomics in mechanized cut to length (CTL) forest harvesting. The concept integrates augmented reality (AR) visualization and mobile LiDAR sensing into a head-up hologram display (HUD) system that projects environmental information directly into the operator's line of sight. Grounded in gamification principles, such as immediate feedback, improved situational awareness, and increased engagement, the system aims to support operators during complex work tasks that require simultaneous attention to machine control, timber quality assessment, and environmental considerations. A field experiment was carried out in eastern Finland, using a John Deere 1170G harvester equipped with an externally mounted Ouster OS0-128 LiDAR sensor and an in-cabin holographic HUD. The test involved the felling of 60 pre-marked Scots pine (*Pinus sylvestris*) trees under thinning conditions.

Real-time tree detection and diameter estimation were achieved through a LiDAR-based processing pipeline incorporating spherical projections and a YOLOv8s-seg instance segmentation model trained on 665 labelled images. Tree positions in three-dimensional space were derived by clustering point cloud data using DBSCAN, while diameter at breast height (DBH) was computed from circle fits applied to horizontal point cloud slices. Detected tree locations and DBH estimates were mapped to HUD pixel coordinates through geometric calibration and homographic transformations, enabling the operator to view holographically projected tree indicators aligned with the external forest environment.

The system demonstrated reliable performance in dynamic operating conditions, correctly projecting tree locations and preliminary DBH estimates for most of the test duration. However, intermittent detection errors and the need for periodic recalibration highlighted the challenges of maintaining stable alignment between the LiDAR sensor, HUD virtual image plane, and operator eye position. Operator workload was assessed using the NASA Task Load Index (NASA TLX), yielding a low mean score of 2.8, indicating minimal added cognitive strain. Post-test interviews further revealed generally positive attitudes toward the system's potential for enhancing situational awareness and decision support.

Overall, the results demonstrate the feasibility of implementing holographic real-time environmental visualization in CTL harvesting but underscore the need for refinement in system alignment, data presentation, and ergonomic integration. Future development should focus on optimizing calibration procedures, improving visual clarity, and designing gamified elements that support operator performance without increasing cognitive load.

Keywords: Ergonomic; Assistance; Harvesting; YOLOv8s-seg

Mechanised harvesting of shrubland biomass from *Cistus laurifolius* formations in Soria (Spain): operational performance, yields and losses

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Cistus laurifolius (rockrose) biomass was harvested in a mechanised operation at CEDER-CIEMAT (Cubo de la Solana, Soria, Spain; mean internal transport distance for the harvested biomass ≈ 3.50 km round trip). The work was carried out in six plots grouped into two age classes (three young-rockrose plots and three old-rockrose plots), allowing performance and losses to be reported separately for each stand type while keeping an overall operational approach. Harvesting was performed with a Valtra T194D forestry tractor (154 kW) equipped with reverse-drive (TwinTrac) and forestry protections, operating a López Garrido TBA 2300 shredder-harvester powered by the PTO and fitted with swinging hammers. During operation, the implement cuts and shreds the shrub layer. The shredded material is moved to an on-board tipping container coupled to the tractor, where the load is accumulated. The container has a nominal capacity of 5 m³; in day-to-day operation, a typical full load was around 1,000 kg of fresh biomass (field estimate). Once filled, the unit travels to the unloading point and the biomass is discharged by tipping the container. This work pattern integrates cutting, comminution, loading and internal transport with a single operator, and time study/recorded operational times allow productivity to be expressed both for harvesting time only and for total operational time including travel and delays.

Across all six plots, total recovered production reached 23.5 t of dry matter (tDM). Average productivity was 1.52 tDM h⁻¹ when considering harvesting time only, and 0.76 tDM h⁻¹ when total operational time is accounted for (including travel and delays). Area-based recovered yield differed strongly by stand age: 3.82 tDM ha⁻¹ in young rockrose and 8.38 tDM ha⁻¹ in old rockrose (overall mean 4.78 tDM ha⁻¹). In addition to recovered biomass, two loss components were quantified: “unharvested” biomass (material left uncut due to operational or geometric constraints, such as very low material or inaccessible stems) and “lost” biomass (material that is cut but not recovered and therefore does not reach the container). In old rockrose, mean unharvested losses were 0.52 tDM ha⁻¹ and mean lost losses were 1.91 tDM ha⁻¹; expressed as a share of the considered total potential (recovered + losses), these represent 4.8% and 17.7% respectively, with 77.5% effectively recovered. In young rockrose, mean unharvested losses were 0.27 tDM ha⁻¹ and mean lost losses were 0.82 tDM ha⁻¹; as percentages of total potential, they account for 5.6% and 16.6%, with 77.8% recovered. These values indicate that the dominant inefficiency is associated with post-cut recovery rather than with the fraction that remains uncut, and they provide a quantitative basis to prioritise improvements in the harvesting head and in operational logistics (unloading and internal hauling), which directly influence the difference between harvesting-time productivity and total-time productivity.

Keywords: Shrubland, biomass, harvester, *cistus*

Integrated mechanical harvesting of gorse (*Ulex europaeus*) in Cantabria–Spain: productivity, costs and harvesting efficiency under contrasting stand conditions

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A pilot operation was carried out to mechanically harvest gorse (*Ulex europaeus*) in Reserva del Saja, Cantabria–Spain, at two selected sites: Riente and Cruz de Sopeña. The aim was to implement and evaluate a shrub biomass extraction treatment using a single-pass system that cuts, shreds and pneumatically conveys the material into a front-mounted container, while documenting operational performance, costs and harvesting efficiency under contrasting stand conditions.

The harvesting chain consisted of a 200 HP Valtra tractor coupled to a López Garrido TBA 2300 shredder-harvester. The machine integrates a horizontal drum (40 swinging blades) to cut standing gorse and initiate comminution, followed by an auger and a turbine that propel the shredded biomass through a duct into a suspended container mounted on the tractor's front three-point hitch. Cutting was performed above ground level to reduce soil contamination, and loads were tipped at the plot edge. The container volume was 5 m³. The transport distance was very short (about 200 m), so the focus was placed on harvesting performance rather than long-distance logistics.

The two stands differed markedly in structure and biomass availability. Mean gorse height was 157 cm in Riente and 252 cm in Cruz de Sopeña, while canopy cover fraction was 66.5% and 92.5%, respectively. These differences translated into contrasting harvesting outputs. Riente delivered 12,129 kg of fresh biomass and 4,924 kg of dry biomass over 287 minutes of productive harvesting time, across 9,800 m² treated, corresponding to 5.02 t dry matter per hectare. Cruz de Sopeña produced 31,814 kg fresh and 13,966 kg dry biomass over 501 minutes, across 6,700 m² treated, equivalent to 20.85 t dry matter per hectare.

Productivity in mass terms reached 1.03 tDM per productive machine hour (PMH) in Riente and 1.67 tDM per PMH in Cruz de Sopeña. Area productivity was 0.20 ha per PMH in Riente and 0.08 ha per PMH in Cruz de Sopeña, reflecting the heavier, denser vegetation and the associated reduction in forward speed in the high-biomass site. Harvesting efficiency, defined as harvested biomass divided by estimated standing biomass before treatment, was 57.43% in Riente and 70.27% in Cruz de Sopeña. The uncollected fraction measured after harvesting was 3.72 tDM/ha in Riente and 8.82 tDM/ha in Cruz de Sopeña, representing 42.6% and 29.7% of the total biomass involved (harvested plus uncollected), respectively.

Using an hourly machine cost of 100 € per productive machine hour, unit costs were 97.14 €/tDM and 488.10 €/ha in Riente, and 59.79 €/tDM and 1,246.27 €/ha in Cruz de Sopeña. The denser stand reduced the cost per tonne through higher throughput, even though the cost per hectare increased due to the larger biomass stock treated. Overall, results show that the same harvesting concept can deliver substantially different performance depending on shrub height, cover and site roughness, and they highlight the importance of matching machine settings and operational strategy to stand structure when targeting efficient gorse biomass extraction at short transport distances. New demonstrations will be carried out within the BIOTER-LAB project in 2026 and 2027.

Keywords: Ulex; biomass; harvester; shrubland

A GIS and Literature-Based Approach for Regional Shallow Landslide Susceptibility Assessment

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Using geotechnical engineering principles to assess slope stability typically uses a factor of safety to define the ratio of resisting to driving forces along a potential failure surface. Accurate estimation of the Factor of Safety is central to evaluating shallow landslide susceptibility, yet field-based measurements of soil strength are rarely available across steep, remote terrain. This challenge is particularly evident in New Zealand's erodible hill-country. To address this limitation, this study develops a reproducible GIS- and literature-based workflow for computing factor of safety using environmental rasters and published geotechnical parameters, without requiring any in-situ testing.

To demonstrate the efficacy of the method, a case study area was selected in New Zealand where major storms triggered numerous shallow landslides in a plantation forestry area accurately mapped by forest owners.

The results demonstrate that a transparent, coding-based approach can generate physically interpretable FS estimates suitable for regional-scale screening in data-limited environments. The workflow establishes a foundation for future hybrid models in which FS-derived indicators can support, constrain, or enhance machine-learning landslide susceptibility frameworks.

Keywords: Slope Safety; Landslides; Geotech;

Compaction Force Using a Hydraulic Excavator Bucket

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Forest road networks are essential infrastructure supporting mechanized forestry operations. These roads must be sufficiently stable to ensure the safe operation of forestry machines. In Japan, many forests are situated on steep terrains, where access by forestry machines is not possible without properly constructed roads, making it necessary to construct narrow roads at high density. Today, an operational system is widely implemented in which machines operate on this constructed road network. Because these roads are primarily earth structures, proper compaction is crucial to maintaining road stability, particularly during construction, especially when filling work is involved. Hydraulic excavators are widely used worldwide for compaction in forest road construction.

Compaction using hydraulic excavators is carried out not only by crawler tracks but also by beating the ground with the excavator bucket. In particular, bucket compaction is used in areas where sufficient compaction cannot be achieved solely with crawler tracks, such as road shoulders, areas between tracks, and slopes. This operation is essential for achieving uniform compaction of filling materials.

In the field of Civil Engineering, studies on soil compaction have focused on compaction machinery such as vibratory rollers and rammers, where stress distribution within the ground during compaction is measured and compaction characteristics have been clarified. In contrast, research in forestry has lacked such investigations into stress distribution and compaction characteristics. Instead, it has mainly evaluated the effects of compaction from tracked or wheeled vehicles on soil properties. Studies focusing on these effects on soil properties have provided important insights into maintaining forest road networks and for reducing the impacts of machine traffic on soil properties. However, most of these studies have focused on the condition of the road structure or soil after compaction and have not mechanically clarified the “compaction force” applied to the ground by machinery during forest road construction. In particular, although compaction using a hydraulic excavator bucket is widely applied in practice and plays an important role in forest road construction, no studies have quantitatively evaluated the compaction force generated by the bucket’s impact.

The objective of this study is to quantitatively clarify the dynamic compaction force produced by a hydraulic excavator bucket. To achieve this, a measurement system incorporating multiple load cells was developed, and the compaction force generated during bucket impact was measured. This study aims to provide a scientific understanding of excavator-based compaction and to support the development of effective compaction methods for forest road construction.

Keywords: forest-road-construction; spur-road; contact-pressure; load-cell

Recent status related to forestry work in Japan

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In recent years, Japan's timber supply has been on the rise. The timber supply in 2023 was 34,259,000 m³, an increase of nearly 60% over the past 10 years. Forestry production activities require the presence of workers. The purpose of this study is to find ways to further promote forestry production activities by analyzing the current state of forestry labor from several perspectives.

Therefore, the author conducted research and analysis from the perspective of the current state of Japan's forestry industry, forestry labor force, and forestry working environment. The author focused on occupational accidents as the working environment.

In Japan's forestry industry, problems in the silvicultural process include an increase in abandoned forest land and the high cost of reforestation work, while problems in the logging process include high costs for logging, inefficient work, low profits for forest owners, and the dangers of forestry work. The number of forestry workers, which was 126,000 in 1985, has now fallen to 44,000. Comparing 1985 and 2020, the number of silvicultural workers has decreased by 76% and the number of timber logging workers by 56%. A shrinking and aging workforce, coupled with a long-term slump in timber prices, have been major challenges. The Forestry Agency launched a human resources development support program for new employees in 2003. By 2023, 20,400 people had been employed in forestry through this program. While the forestry industry once had a large female workforce, this number has declined significantly over time. The decline in silvicultural workers is particularly notable. The number of timber harvesting workers has also gradually declined, falling below 500 in 2020. Women's employment in the forestry industry is believed to play a major role in revitalizing the industry, and it is necessary to identify and resolve the issues that will increase this number. The results showed a decrease in the number of casualties due to accidents in the forest industry over the long term, but reveal that this decrease is due to a decline in forestry production works. The author compared the incidence rate of accidents with that of other industries. Since 1987, this index has remained unchanged, but that for forestry work shows the highest value. In 2019, the incidence rate was 20.8 for forestry, about 9.5 times the average for all industries. We believe that in order to further ensure safety in forestry work, it is effective to promote the development of advanced mechanization, information and communication technology, safety education, improvement of working conditions, and analysis of work-related accidents.

In Japan, it is necessary to promote forestry as an attractive growth industry by utilizing forest resources. In order to revitalize the forestry industry in the future, it is important to use new technologies such as geospatial information, ICT, and AI to develop forest management plans and efficient and safe work plans, and there is a need to enter the forestry industry and develop human resources with such knowledge and skills.

Keywords: forestryactivities; forestryindustry; laborforce; workingenvironment;

Time structure and efficiency of timber harvesting using harvester, depending on the terrain's surface unevenness

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In Central and Eastern Europe, mechanical timber harvesting is becoming increasingly important every year. In most cases, it dominates other levels of technology in timber harvesting. The aim of the study was to investigate the efficiency of machine harvesting in terms of productive work time in productive stand. Timber harvesting was carried out using a Rottne H-14 harvester. The study examined measures of work efficiency depending on the direction of machine movement and the layout of skid tracks (parallel and perpendicular) in relation to linear terrain irregularities resulting from the preparation of very wet soil for planting using an excavator. The terrain irregularities were ditches between beds on which three rows of trees were planted. The average depth of the ditches was 0.75 m, and the width at the top was 2.10 m. The study was conducted in a 25-year-old pine stand that had undergone early thinning. The measures of efficiency were time consumption [minm⁻³] and productivity [m³h⁻¹] in productive work time. For each direction of harvester movement, 200 work cycles were observed and measured. The average time consumption in the parallel and perpendicular directions was 8.2 and 7.9 minm⁻³, respectively, while the average productivity was 7.3 and 7.6 m³h⁻¹. No significant differences in the efficiency of timber harvesting were found depending on the direction of movement of the machine in relation to the described linear irregularities.

Keywords: time-consuming; productivity; thinning; unevenness

Load Distribution and Dynamic Forces in Guylines of European Tower Yarders

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Tower yarders have been a well-established harvesting technology in European mountain forestry since the 1960s. Despite their long-standing practical relevance, the dynamic tensile force of the cable system under real operating conditions remains insufficiently understood. While in situ measurements of skyline forces are available, the contribution of guylines is commonly overlooked, even though guyline forces is fundamental to tower stability and anchorage safety. This lack of empirical evidence constrains the mechanical assessment, dimensioning, and safe installation of cable yarding systems.

The aim of this study was to quantify the dynamic forces response of skyline and guylines under operational conditions and to identify the work phases associated with critical peak loading. Tensile forces were recorded at a sampling frequency of 100 Hz on four cable yarder installations in Styria, Austria. More than 300 work cycles were monitored with more than 25 hours of productive machine operation. Tensile forces were measured in the skyline and in all four tower guylines. This enables an analysis of the working phases within the entire cable system.

Mean guyline forces ranged from 3 to 51 kN. Under certain system configurations, however, guyline forces reached up to 70% of the concurrent skyline tension. When adequate pretension was applied, guyline forces exhibited an approximately linear relationship with skyline tension, indicating a stable and mechanically consistent response of the guyed tower system. By contrast, insufficiently pretensioned guylines displayed distinctly non-linear load responses, pointing to irregular force sharing and reduced structural predictability.

The most critical loading conditions were observed during lateral skid and during the inhaul phase. Lateral skid produced abrupt force increases that were primarily associated with breakout and rapid load transfer. The inhaul phase, in turn, generated pronounced dynamic oscillations within the cable system. Frequency-domain analysis further showed that the dynamic response was dominated by low-frequency oscillations below 1 Hz.

The findings demonstrate that dynamic peak forces in both skyline and guylines must be explicitly considered in the mechanical design, pretensioning strategy, and safety assessment of tower yarder installations. In particular, guyline forces should no longer be regarded as a secondary aspect of system behaviour, since they can reach structurally relevant magnitudes and substantially influence the overall stability of the installation.

Keywords: cable; force; safety; anchoring

Blockchain technology as a traceability tool in the Wood Supply Chain

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This research is carried out within the national project Tech4You – Technologies for climate change adaptation and quality of life improvement, funded by the National Recovery and Resilience Plan. Against a global backdrop of growing attention to illegal timber sourcing and the need for clearer information on wood logistics, movement, and marketing, the study examines a blockchain-based electronic traceability system designed to increase transparency and safety across the wood production and processing chain. The proposed solution uses a decentralized, distributed ledger, made available to all stakeholders via a secure digital platform, to record, access, and share validated information on timber origin and every processing stage—from tree harvesting to sawmill operations. Thanks to the immutability and visibility of recorded transactions, blockchain can reinforce trust among actors (producers, processors, and end users) while limiting fraud risks such as document manipulation or material substitution. Beyond transparency, the system can support sustainability by improving monitoring of forest resources and enabling verification that timber comes from responsibly managed sources. Overall, the study shows how digital traceability frameworks can strengthen accountability and sustainability in the wood sector, while reducing the time and costs typically associated with manual inspections and conventional certification procedures.

Keywords: Certification, Wood quality

Long-Distance Timber Transport on Curved Mountain Roads: Operational Cycle Assessment

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In Europe, long-distance road transport of timber is commonly carried out by trucks, either as single units or in truck–trailer configurations. In mountainous forests characterized by rugged terrain and frequent curves on forest roads, tractor–semi-trailer combinations often face access constraints at roadside landings. Under such conditions, single trucks and trucks with trailers represent the most feasible options for transporting assortments to customers.

To investigate these haulage solutions, time-and-motion studies of work cycles were conducted under operational conditions. Field data were collected for a single truck and for a truck with trailer in the Lesidren State Forest Range (northwestern Bulgaria). In addition, a third case study was included in Calabria (southern Italy), where a single timber truck operated in a mountainous context with curved road geometry, transporting roundwood assortments. The work cycles followed the same operational scheme as in the Bulgarian observations, enabling a coherent comparison across study areas.

For each vehicle and site, work cycles were analysed by distinguishing productive elements (loading, travel loaded and unloaded, unloading) from delays, and by evaluating payload, productivity, and cost behaviour at the cycle and shift levels. The study highlights how local road constraints and vehicle configuration influence operational efficiency and economic performance in long-distance timber haulage. Overall, the findings support the need to match transport solutions to forest-road conditions and to use systematic cycle monitoring to improve planning and cost control.

Keywords: payload; transportation; time-motion; forest-operation;

Rut depth and Stand damage analysis after Winch-Assist harvesting

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Winch-assisted harvesting technology is becoming increasingly common in Alpine countries and in forests on steep terrain. However, research into the impact of this technological system on forest soil and stands remains limited. In a study conducted at three different sites, we measured several parameters on sample profiles perpendicular to the skid trail, including rut depth and compaction, skid trail slope and width, number of machine passes, coverage of the trail with logging residues, residue thickness, and soil water content. The average rut depth of skid trails across all sites was 14.9 cm, with the average depth in Žetale at 23.1 cm, in Log at 14.9 cm, and on Pohorje at 13.1 cm. We found that rut depth increases statistically significantly with the number of machine passes, and that higher soil water content generally increases rut depth, although the effect is small. The slope of the skid trail has a significant effect in Žetale and Pohorje, as terrain slope increases, rut depth increases only in Pohorje, while it decreases at the other two sites. We also analysed stand damage on circular sample plots of 100 m², distributed systematically across the site. The proportion of damaged trees was highest in Pohorje (52.5%), followed by Log (51.7%), and lowest in Žetale (38.6%). The average size of damage was highest in Pohorje (230.2 cm²), 178.9 cm² in Žetale, and lowest in Log (172.3 cm²). Most damage occurred on the stems, with the least in the crowns of standing trees. We found that tree species and diameter at breast height significantly influence the occurrence of tree damage. Compared to non-assisted mechanised harvesting, winch-assist technology is reported to cause less damage to forest floors due to the use of a winch and smaller wheel ruts, although this depends on several factors. The results of our study, compared to others that also examined winch-assist harvesting, show that average wheel rut depths are greater in most cases. A comparison of studies on stand damage during mechanised harvesting without winch assistance with our results showed, that the proportion of damaged trees was higher, while the average size of damage was lower at our sites than in some other studies. As has been established, soil and stand damage is influenced by many different factors, so further studies at different research sites are needed to obtain a better assessment of the suitability of winch-assisted harvesting technology for specific working conditions.

Keywords: Winch-assist-harvesting; rut-damages; stand-damages; steep-slopes

Integrating Forest Roads into Nature-Based Flood Risk Management: From Evidence to Practice in the AquaSilva Project

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Forest roads are one of the most important components of the infrastructure for forestry in Austria and Europe. They ensure operational efficiency in forest management and the provision of essential ecosystem services, particularly with regard to preserving their multiple functions for society. Forest roads also have a significant impact on the generation of runoff within forested catchments and in downstream areas.

The hydrological effects of forest roads on runoff generation remain insufficiently quantified and depend on various factors. These include construction materials used, cross-section design, longitudinal slope, and roadside drainage design, as well as regular and proper maintenance of forest road networks. Furthermore, planning and decision-making processes must incorporate sufficiently detailed information to improve understanding of the hydrological effects on runoff formation and flood risk.

This paper summarizes the empirical evidence from previous studies and outlines the conceptual and methodological approach of the AquaSilva research project, which systematically integrates forest infrastructure into nature-based flood risk management.

The AquaSilva project (2026–2029) is developing transferable methodologies and decision-support tools to implement decentralized water retention measures within forest infrastructure. Through iterative model development (ZEMOKOST and RAVEN), field monitoring campaigns and stakeholder engagement, the project will create practical guidelines and a comprehensive catalogue of measures for forest practitioners and planners. The work packages systematically address the evaluation, spatial design and impact analysis of retention and infiltration elements along forest roads, including skid trails, explicitly considering construction materials, location within catchments and integration into operational forest management.

The project's outputs will provide standardized tools for cross-sectoral planning, enabling forest engineers to select, design and maintain infrastructure that enhances operational efficiency and contributes to flood risk mitigation. This integrated approach bridges the gap between empirical hydrological evidence and practical implementation, positioning forest infrastructure planning as a key component of resilient, nature-based water management in mountain regions.

Keywords: Hydrology; Retention; Drainage; Flood

Digitalized and (semi-) automated design of cable roads by combining different sources of geospatial data and high precision mechanical analysis

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Cable-based technologies have been a backbone for harvesting on steep slopes for decades. The planning of a cable road is a complex task. It essentially comprises the definition of the start and end points of a cable road, as well as the intermediate supports. It must ensure permissible forces (in particular skyline tension) are not exceeded, maintain sufficient clearance between the load path and the ground, identify suitable anchor trees, and minimise intermediate supports where possible.

On the other hand, for ergonomic and silvicultural reasons (work safety, damages to the forest), the skyline should be as high as possible. In practice, finding a solution is often iterative; especially for long lines, where several attempts may be needed to identify a good layout.

We present the QGIS plugin SEILAPLAN which supports cable-road design by automatically searching for the optimal cable road layout while also allowing manual editing. Embedded in a GIS system, it provides direct elevation data and can integrate individual tree data and vegetation height models to identify suitable supports and anchor trees already at the planning stage. The plugin is tailored to Central European conditions and assumes a standing skyline (fixed anchored skyline at both ends). Skyline mechanics are computed using a near-catenary method. When testing the feasibility of the cable road, care is taken that 1) maximum permissible skyline stresses are not exceeded, 2) minimum distance between the load path and the ground is maintained, and 3) for gravity systems, the load path meets a minimum gradient. The developed method calculates the load path curve and the resulting forces with a high accuracy.

The presented QGIS plugin SEILAPLAN is a key step towards digitalized forest operations on steep terrain and is already widely used in Switzerland and beyond. By 2026, version 3.7.1 is available, offering major further development in terms of functionality and user-friendliness compared with the initial version. The poster highlights and focuses on the most actual developments and gives an outlook on further planned features.

Keywords: Seilaplan; Cable_Logging; GIS; DSS

Defining Terrain Trafficability Based on High Spatial Resolution DTM

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Terrain trafficability affects average skidding distance (ASD) calculations through economic impact and environmental restrictions during skidding operations. This research tested the possibility of using an unmanned aerial vehicle (UAV) equipped with a LiDAR sensor in determining inaccessible forest areas for skidding operations based on restricting terrain slope and/or ground obstacles. Areas restricted for skidder mobility were determined with the high spatial resolution digital terrain model (DTM) that was the result of an airborne laser scanning (ALS) survey. Pixel size of tested DTM was 0.25 m. Research was conducted in management unit Belavine, Republic of Croatia. Terrain of research area can be characterised as steep. Data from the ALS survey was compared with the data from a terrain field survey where permanent and temporary watercourses were highlighted together with steep water bank slopes where skidders' mobility is impossible due to its dimensional characteristics. The analysis of non trafficable terrain was performed in the ArcGIS programme package. Although, some discrepancies between the methods arose, the results indicate the possibility of using a high spatial resolution DTMs to determine terrain trafficability for skidding operations as oppose to labour intensive and time-consuming field data surveys. Future research must include other parameters that limit skidders' mobility, as well as the automation of the analysis by creating a sufficient GIS plug-in.

Keywords: timber_extraction; ALS; harvesting_operations; ground_obstacles

From Proof of Concept to Robust Models: Data Challenges in Deep Learning Based Forest Road Monitoring

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Mobile sensing and deep learning approaches offer strong potential to modernize forest road inventories and support applications such as technical road classification, operational planning, and maintenance decision support. Over the past four years, we have developed and validated RoadSens, a vehicle mounted proximal sensing platform that combines stereo vision, GNSS based geo referencing, and learning based perception to extract geometric and condition related information from forest roads. Multiple case studies have demonstrated the technical feasibility of the approach and its applicability across a range of operational use cases.

While the sensing and geo referencing concepts have proven robust, this poster focuses on the main remaining bottleneck for further system improvement: the availability, diversity, and quality of training data for object detection models, particularly for road surface deterioration and damage features relevant to maintenance planning. Current models can reliably detect more uniform features, but performance degrades for irregular, heterogeneous, and context dependent damage types such as wheel ruts, erosion features, or mixed degradation patterns. These limitations are not primarily methodological, but data driven.

Our experience with RoadSens shows that model performance is highly sensitive to:

- (i) variability in road construction types and materials
- (ii) vegetation development and seasonal conditions,
- (iii) differing definitions of “damage” across regions and user groups, and
- (iv) class imbalance and annotation ambiguity in training datasets.

At the same time, the modular design of the RoadSens pipeline makes it well suited for continuous learning, provided that larger, more diverse, and better curated datasets become available.

The central message of this poster is therefore twofold: the concept has been proven, but scaling and operational robustness depend on shared data efforts. We propose using this contribution as a starting point for discussion with fellow researchers and practitioners on how to collaboratively build joint, preferably open and standardized datasets for forest road geometry and damage features. Such datasets could significantly accelerate the development of transferable models and support a wide range of applications beyond RoadSens, including maintenance prioritization, accessibility analysis, and infrastructure monitoring.

The poster explicitly invites exchange on dataset design, annotation strategies, quality control, and governance models to foster community driven data resources for forest road research and operations.

Keywords: training-data; open-datasets; road-deterioration; maintenance

Cost-sensitivity of forest peatland timber harvesting methods

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Forested peatlands and forest wetland areas provide a large variety of ecosystem services and support biodiversity. Thus, particularly in the implementation of national strategies to mitigate climate change and enhance biodiversity, these areas are increasingly becoming the focus of management action. Consequently, they require inclusive forest management plans to guarantee the provision of all services now, but also in the future. One important element to be considered is the provision of timber and thus the assignment of best suitable harvesting methods.

In a decision-making framework aimed at identifying the optimal harvesting system, which is needed for setting up wholesome management plans, it therefore makes sense to include economic aspects.

In this study, we present a harvesting-cost sensitivity analysis for selected harvesting-systems, designed for peat- or wetland harvesting operations. The results allow a direct comparison of multiple cost-effects of productivity and machine-cost-calculation parameters, helping to identify a suitable portfolio of alternative harvesting options and to reveal their optimization potential.

Keywords: peatland; cable yarder; harvesting-costs

Integrating 360-Degree Video Photogrammetry into Individual-Tree Growth Simulations: A New Pipeline for Precision Forest Management

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Forest simulation input typically relies on data derived from conventional field inventories. However, field inventory surveys are often characterized by labor intensity, time constraints, and inherent scalability limitations. In contrast, recent advancements in remote sensing and digital technologies have significantly improved the ability to collect data in forested areas. In this context, integrating forest simulations with high-resolution data could lead to a methodological shift in simulating a range of management scenarios.

High-resolution point cloud data provides accurate information about current forest conditions and tree characteristics, which can be incorporated as inputs for simulations. We use the spherical camera Insta360 Pro 2 to acquire 360-degree video data in forest areas. Our photogrammetric pipeline generates a precise reconstruction of the 3D structure of the forest directly from the captured videos. This 3D reconstruction enables an accurate assessment of each tree's characteristics within a specified forest stand, thereby eliminating the need for traditional inventory methods.

The single-tree features (such as diameter at breast height and tree position) extracted from such high-resolution reconstructions can serve as a foundational input for forest growth simulations. This advancement has the potential to improve the precision of the simulations by providing detailed data for any given forest area, allowing us to simulate tree growth, competition, and mortality on a per-patch basis. Consequently, we could gain deeper insights into forest dynamics under various intervention scenarios and climate change conditions, strengthening the basis for adaptive management. Finally, by marking trees of interest virtually, we could enhance planning activities in forest operations.

Keywords: 3D reconstruction; videogrammetry

Different Wood Damages from Seven Harvesters

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In Sweden, approximately 75 million m³ of timber are harvested each year, predominantly using single-grip harvesters. Maintaining wood value is essential, and the process begins already at the harvesting stage. The Wood Value Trials is a Swedish comparative study evaluating seven large harvesters from different manufacturers. Each machine felled and processed 30 Norway spruce stems, producing roughly 150 logs per harvester. This study is a part of that trial and focuses specifically on wood damage arising during bucking. It is important to minimize damage levels, as part of the wood is wasted at the saw mill if containing bucking splits, stud- or debarking damage, affecting the economic value.

The three types of wood damage were studied separately:

Splits resulting from bucking were assessed at both ends of each log, except at the butt end of the first log (the felling cut). Splits were measured by cutting discs with a chainsaw, striking the lower third of each disc to detect any hidden splits, and continuing to cut discs until the split terminated. The total split length was calculated by summing up the thickness of the discs. The radial position of the split was recorded as the distance from the log center.

Stud damage caused by the feed rollers was recorded at the top end of the log. Damage depth was measured by cutting across a stud mark with a knife and measuring, in millimeters, the deepest affected fiber.

Bark peeling caused by the delimbing knives was recorded at the top end of the log. The extent of bark damage was measured by placing a measuring tape around the log's perimeter and recording the width of the peeled area. Damage was classified as either 50% depth or 100% depth (the latter indicating complete removal of inner bark and exposure of wood).

Differences in damage levels were compared among the seven harvesters. The preliminary results indicate differences between all three damage types, suggesting that harvester head design has a measurable effect on wood value. These findings imply that further technical development of harvester heads is important to improve value recovery and reduce revenue losses associated with wood damage.

Keywords: Harvester; Value; Bucking; Damages

SingleTree: Explore the Living Lab Value Chains

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SingleTree is an EU-funded project that develops optimized single-tree value chains to enhance climate change adaptation, forest resilience, multifunctionality, and the cascading use of woody biomass within precision forestry systems.

These value chains are enabled by innovative forest monitoring and management strategies that integrate (1) AI and remote sensing, (2) adaptive single-tree-level management solutions, (3) intelligent machines for implementing single-tree operations, and (4) improved traceability and the ability to predict wood quality early in the value chain as a foundation for optimized biomass supply.

To connect these individual technical solutions into fully integrated digital value chains, SingleTree demonstrates the project's innovations in three Living Lab Value Chains (LLVCs) located in northern, central, and southern Europe. They serve both as demonstration environments for connected, optimized single-tree value chains and as an empirical basis for environmental assessment of the proposed solutions.

The poster presents the three LLVCs and provides insights from the project's first year, which focused primarily on data collection, including, for example, the deployment of the Kelluu airship in the northern case.

Keywords: optimization; traceability; multifunctionality; digitalization

Classification of forest roads in the province of Quebec using remotely sensed data

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More than 90% of the forest territory in Quebec is publicly owned, and as is the forest road network, which is funded through the user-payer principle. There is a publicly available database (AQRéseau+) that contains information on forest roads and their characteristics. Since there are more than 450 000 km of forest roads in the province of Quebec, this database is useful for forest practitioners to support managerial decisions. Accurate forest road inventory is essential for efficient planning of forest operations and for maintaining better control over operational costs. A precise inventory, categorized by road class, enables forest stakeholders to plan their activities appropriately and allocate resources where they are most needed. In contrast, the absence of a reliable inventory often results in the abandonment of certain road sections. Once abandoned, these roads receive little to no maintenance, which accelerates their degradation and increases the risk of environmental impacts such as erosion, sedimentation, and watercourse disturbance.

Currently in Quebec, this data on forest roads is not actively updated beyond the initial input, which limits its usefulness. This project aims to develop a methodology to automate detection and classification of logging roads to have a more reliable knowledge of the forest road network using remotely sensed data.

This project carried out for two regions of the province of Quebec in Canada, the Capitale-Nationale and Gaspésie. It was divided into two phases: first, the detection of existing roads, and then the classification of these roads. First, a literature review was carried out to choose the detection model to be used. This literature review focused mainly on road-detection models using LiDAR technology and their limitations. It also made it possible to identify what kinds of classifications these models can perform. Once the literature review was completed, the modification of an already existing road-detection model was carried out. The original model could detect forest roads and surface water using segmentation and deep learning algorithms. The modified model was applied to forests whose characteristics are representative of the reality of the Capitale-Nationale and Gaspésie regions. Thus, it was tested in both coniferous and deciduous areas. It located roads considered still usable and classified them according to the chosen characteristics. Once the roads were classified, photo interpreters validated the model.

The preliminary results of this project will be presented at the conference.

Keywords: Characterization; Road; Model; Automatic

Multi-use road networks: Tactical management framework

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In most wood supply areas, forest roads form vast infrastructure networks that structure socio-economic activities, territorial access, and ecosystem organization. In Québec, Canada, these roads now extend over 485,000 kilometers in public forests, demanding coordinated management by forestry industrials, recreation organizations, First Nations, and municipalities. Yet only twenty percent of these roads are maintained, and one-third are still used which leads to wide ecological changes and unregulated access. Despite the availability of numerous planning tools, their use remains limited in practice. Consequently, decisions on road development are still largely based on the experience and intuition of forest engineers. Similar dynamics are observed in many forested regions worldwide. The objective of the study is to develop a comprehensive management framework that enables practitioners to plan, prioritize, and optimize forest road networks over a medium-term planning horizon.

Two case study regions were selected to operationalize the management framework using CAROPER, a spatial and visual decision-tool based on a hexagonal grid. CAROPER aggregates forest resources data into indices and displays them using graduated color scales. While originally designed for strategic silvicultural planning, the framework was extended in two directions. First, social occupancy indices derived from land-use data were incorporated to assess the actual occupancy of the network. Second, road network orientation and connectivity were incorporated into the hexagonal analytical structure. Coupling spatial indices with network configuration enables the identification of priority levels for each road segment. This explicit network rationalization using the tool facilitates tactical decision-making regarding maintenance optimization, closure, repair or decommissioning.

The methodology follows an iterative sequence: (i) spatial analysis using the CAROPER framework, (ii) selection of road segments based on multi-use performance and connectivity, (iii) application of a conceptual allocation model inspired by Transaction Cost Theory to structure maintenance cost distribution among stakeholders, and (iv) consultations with stakeholder to validate feasibility and governance considerations. Preliminary results indicate that the network is not effective in addressing all uses across the territory and that connectivity indices significantly improve maintenance prioritization compared to volume-based approaches alone. Ultimately, the proposed method will serve as an integrative decision-making tool to help maximize the value of public forests for a variety of uses.

Keywords: Forest-road-networks; Multi-use; Tactical-planning; Decision-making-tool

Advancing Precision Forestry through Augmented Reality-Based Tree Visualisation

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As the forestry sector transitions toward the era of Forestry 4.0, the integration of digital planning into physical field operations remains a critical bottleneck. Traditionally, in high value thinning tree selection and marking, essential for sustainable forest management and selective harvesting, rely on manual application of spray paint. This analog process is not only labour-intensive but also creates a significant disconnect between digital inventory databases and the actual environment. This poster explores the transformative potential of Augmented Reality (AR) as a solution to bridge this gap by enabling the direct, real-time visualisation of digitally marked trees within the forest stand.

By leveraging high-precision Global Navigation Satellite Systems (GNSS) combined with Simultaneous Localization and Mapping (SLAM) algorithms, AR headsets and mobile devices can project "virtual paint" or holographic indicators directly onto specific tree trunks. This technology allows foresters to perform virtual selections that are immediately anchored to the physical tree, creating a persistent digital layer that is visible to harvester operators and forestry crews. Such a system eliminates the need for physical marking materials, reduces the time spent searching for designated trees in dense undergrowth, and ensures that complex silvicultural prescriptions are executed with unprecedented spatial accuracy.

Furthermore, the implementation of AR-based visualization facilitates a dynamic feedback loop; harvest plans can be updated remotely and reflected instantly in the field, allowing for agile responses to environmental changes or timber market demands. While challenges regarding hardware durability in extreme weather and signal occlusion under dense canopies persist, the transition from physical to virtual marking represents a paradigm shift in forest operations. This study concludes that AR-driven tree visualisation not only enhances operational efficiency and safety but also provides a more sustainable, data-driven framework for managing the forests of the future.

Keywords: AugmentedReality, PrecisionForestry, DigitalTwins, ForestOperations4.0.

Assistance systems for forestry machines

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The complex operation of forestry machines in the forestry work environment places high demands on the machine operator. Inexperienced operators are unable to meet these requirements during their learning phase, resulting in very low productivity during operation. On the other hand, experienced drivers are facing a high workload under the very varying working conditions during long shifts.

Assistance systems offers a high potential supporting both new and experienced forestry machine operators. In this presentation, we will show various assistance system realised in modern forestry machines, integrated in HSM series machines and in HSM research prototypes. This will cover assistance systems for driving, safety, environment monitoring and operating a forestry crane. The goal of these assistance system is to support the operators towards a safe workplace and increasing efficiency and productivity.

Keywords: Assistance systems; forestry machine

Analysis of production costs and transport radius in the forestry sector: A case study in Brazil involving risk modeling

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ABSTRACT. Transportation is a strategic activity in the forestry sector, primarily due to its high impact on timber production costs. In Brazil, this activity, along with timber harvesting, represents a significant portion of the wood production cost delivered to the mill. This study aimed to evaluate the production cost of road forest transportation based on operating distance (forest-to-mill), as well as to define the maximum radius to ensure the economic viability of the transport company. Risk modeling was applied for the economic management of the transport activity, considering transport distance, depreciation, fuel, maintenance, and labor costs as input variables. The triangular distribution was used for economic risk modeling, given its wide application in agricultural science research. A $\pm 10\%$ variation was applied to the input variables for the risk simulation, which was based on the Monte Carlo technique. The average production cost of forest transportation (USD.m³) was adopted as the output variable. Risk was identified when the production cost exceeded the rate paid per tonne transported. The research was conducted at a timber transport company located in the state of Minas Gerais, Brazil. According to the operating conditions and the freight rate paid, the maximum transport radius (round trip) was 149 kilometers, which is very close to the company's actual operating conditions (138 kilometers), indicating that the evaluated company operates with low profit margins. Despite the low project attractiveness, the assessed risk for the transport company remained below 10%. The regression coefficients were significant and directly related to the production cost. The sensitivity analysis allowed for the economic planning of the transport activity, indicating the threshold values for the transport company's economic sustainability.

Keywords: Economy; wood; truck; risco

Biomass Yield and Fuel Properties of Fast-Growing Broadleaved Plantations on Former Agricultural Land in Latvia (Northern Europe)

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Afforestation of former agricultural land with fast-growing broadleaved species represents an important opportunity to increase the supply of renewable forest biomass for bioenergy and bio-based products while contributing to climate change mitigation. As the role of biomass in renewable energy systems and the bioeconomy continues to expand, reliable information on biomass availability and fuel-related wood properties becomes increasingly important, particularly under the climatic conditions of Northern Europe.

Most studies addressing biomass properties have focused on conventional forest stands, while systematic data from plantations established on former agricultural land remain limited. Such plantations differ from natural forests in stand structure, growth dynamics and row-planting patterns, which may influence biomass production as well as key fuel characteristics relevant for harvesting, processing and energy utilisation.

This study analysed above-ground biomass production, moisture content and wood density in 15-year-old plantations of aspen (*Populus tremula*), grey alder (*Alnus* spp.), and willow (*Salix* spp.) established on former agricultural land in Latvia, Northern Europe. Biomass was estimated using field inventory data and species-specific allometric equations. Moisture content and wood density were measured along the stem at 1 m intervals to assess vertical variation, while radial density variation from pith to bark was analysed at each height level.

The results provide new empirical data on biomass yield and fuel-related wood properties of fast-growing broadleaved plantations under Northern European climatic conditions. These findings support improved assessment of biomass resources and contribute to better planning of harvesting operations, biomass supply logistics and efficient utilisation of forest biomass in renewable energy and bioeconomy systems.

Keywords: biomass; plantation, bioenergy, forestry

PlacRoboFoR – automatic forest planting machineholder

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The aim of the project was to develop an autonomous robot for planting forest crops and reforesting reclaimed and post-agricultural land. Unlike traditional planting methods, the advantages of the innovative automated system include: elimination of manual labour – the worker only remotely controls the operation of the machine, increased efficiency – extended operating times, selection of the optimal driving trajectory, reduction of energy consumption – elimination of surface soil preparation in favour of planting, shortening of the technological process – planting with seedlings grown in standard cassettes, increase in crop yield associated with reduced post-planting stress by eliminating the need to remove seedlings from cassettes in advance, causing drying out and crumbling of the root ball, and optimisation of seedling verticalisation and root ball compaction, adaptation to work in unploughed and steeply sloping terrain – use of satellite navigation and automatic levelling systems, potential for system expansion, e.g. retrofitting with working units for crop maintenance.

The drive system of the machine is designed so that each wheel is driven by a hydraulic traction motor and can be independently set at a different angle to the axis of the driving platform, allowing it to move in any direction and rotate around its own axis. In addition, each wheel is mounted on an independent swing arm, which allows the platform to be levelled over a wide range both along and across the direction of travel. The first agrotechnical operation performed by the machine is the preparation of the site by a three-pronged roller. Then, a stake, into which a seedling has been previously placed, is driven into the ground. The innovative design of the stake releases the seedling as it rises and spreads apart. The machine can take 600 seedlings at a time in standard growing trays, placed in a carousel-type storage unit. The manipulator consists of five grippers, whose task is to grasp (by the root collars) the seedlings from one row of the growing container, lift them vertically upwards from the target and move them over the buffer conveyor, into which the seedlings are thrown in order to move them further to the planting stick. This solution increases efficiency by providing time for subsequent manipulator work sequences.

Keywords: planter; automation; container seedlings

Efficiency of timber harvesting with a harvester in fir stands with designated and undesignated thinning

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The aim of this research was to evaluate the effectiveness of timber harvesting in mountainous fir stands undergoing thinning, where trees were either pre-designated for removal by forestry services or selected independently by the machine operator. We hypothesized that differences in stand perception, particularly in terms of areas of visual focus and variability of eye activity, might influence cognitive load and work efficiency. Timber harvesting was conducted using John Deere 1170E harvester. Chronometric analyses were performed, and the operator's visual scene was examined using the Tobii Pro Glasses 2 eye tracker.

The time required for harvesting in stands with undesignated thinning was, on average, 12% greater than in stands with designated thinning. The primary factor contributing to the increased time in the undesignated variant was extended machine passage during stand classification and the operator's careful planning of cuts. Under undesignated thinning conditions, trees with lower volume were harvested. The operator's mental workload was comparable between the two variants. The absence of significant differences in fixation time suggests that the operator maintained a similar level of concentration in both cases, adjusting visual strategies to the task context.

Keywords: timber harvesting; effectiveness

Are battery-powered tools a better option for forest operations, such as sprout selection?

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Eucalyptus coppice management remains strongly dependent on motor-manual operations performed with combustion-engine chainsaws, despite their well-documented environmental and ergonomic limitations. These tools contribute to greenhouse gas emissions and increase operator exposure to noise and hand–arm vibration, raising concerns regarding both sustainability and occupational health. The electrification of motor-manual forest operations has emerged as a promising alternative; however, its performance under real field conditions remains insufficiently quantified. This study presents a field-based assessment of electric motor-manual operations for sprout selection in Portuguese eucalyptus coppice. Conventional operations using combustion-engine chainsaws are directly compared with battery-powered alternatives, including electric chainsaws and electric pruning saws, under representative operational conditions. A multi-criteria evaluation framework is applied, integrating productivity analysis (time-and-motion studies), ergonomic assessment (including hand–arm vibration exposure, noise levels, physical workload, working postures, and perceived discomfort), greenhouse gas emissions quantification, and simplified life-cycle cost analysis. Operational quality is further evaluated through post-operation field inspections of stump characteristics and sprout selection accuracy. The results will provide robust empirical evidence on the technical, environmental, economic, and ergonomic performance of electric motor-manual equipment in silvicultural operations. By explicitly quantifying trade-offs and synergies across these dimensions, this study advances current understanding of the role of electrification in forest operations. The findings will support informed decision-making and contribute to the transition toward low-emission, ergonomically optimized forest operations in the Portuguese forestry sector.

Keywords: productivity; ergonomics; eucalyptus coppice

Validation of KUBIQ Photo-Optical Measurement of Timber Stack Volume

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Accurate and efficient measurement of wood stored in stacks is important for inventory control, logistics, and verification of harvested volumes. This study evaluated whether KUBIQ, a mobile photo-optical application developed by PDSOFT s.r.o., can reproduce a standard field-based reference measurement of stacked wood volume. A manual method of measurement was used as a reference, and calculated stacked cubic meters were used for comparison, meaning the volume of the stack envelope, including voids between pieces and without conversion to solid cubic meters.

The dataset comprised 55 wood stacks measured in the field. For the reference manual method, each stack was measured by its horizontal length, nominal log assortment length used as stack depth, and weighted mean stack height; reference stacked volume was calculated as length x depth x weighted mean height. The same stacks were then recorded with KUBIQ. The app workflow used image capture of the stack face, automatic outline detection, manual checking and correction of the traced boundary where needed, entry of length and stack depth, and app-based calculation of stacked volume. Differences between the two methods were evaluated using bias error, absolute error, relative bias error, and relative absolute error. Because volumes and residuals were not assumed to be normally distributed, method agreement was assessed with Spearman's rank correlation and a Wilcoxon paired test.

KUBIQ showed very close agreement with the reference manual method. Mean volume was 31.4 stacked m³ for the reference method and 31.174 stacked m³ for KUBIQ. Total measured volume differed by 12.8 stacked m³, equivalent to approximately 0.74% of the reference total. The mean absolute error was 1.269 stacked m³, and the median absolute error was 0.710 stacked m³. The relative absolute error averaged 5.07% and had a median of 3.44%. Agreement was very strong (Spearman $r = 0.99$), and the Wilcoxon paired test showed no statistically significant systematic difference between methods ($p = 0.7$). Relative errors were highest in the smallest stacks, where small absolute differences represent a larger share of total volume; from approximately 20 stacked m³ upward, mean relative absolute error was generally around 3-4%.

The observed performance is consistent with published validations of other photo-optical stack-volume software, such as iFOVEA Pro, LogStackPro or Timbeter, where close overall agreement with reference measurements is commonly accompanied by higher relative variability in small or irregular stacks. KUBIQ therefore, appears to behave similarly to comparable available tools. It may serve as a promising option for rapid operational checks, inventory documentation, and image-supported traceability of wood stacks. As with other photo-optical methods, reliable use is best supported by a consistent field protocol, careful image capture, clear visibility of stack boundaries, consistent tracing, and additional verification of very small or irregular stacks.

Keywords: photo-optical-measurement; woodstack; forestry-logistics; stacked-volume

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