

Tree detection accuracy in Pre-commercial thinning stands

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Executive Summary

This white paper presents validation results for the Conifer Vision AI-based tree detection system in pre-commercial thinning stands across northern Sweden. Across 166 RTK-positioned test surfaces distributed over 16 areas in Norrbotten and Västerbotten counties, the system demonstrated strong predictive performance: mean tree height predictions achieved a correlation of $r \approx 0.96$ with field measurements, with an average bias of -3% and mean absolute error of about 13% . Stem density estimates showed a correlation of $r \approx 0.93$, with an average bias of -4.7% and mean absolute error of about 14% . The results indicate that remote sensing-based tree detection can provide operationally reliable height and density information for pre-commercial thinning planning, though additional model training is recommended to further improve accuracy in the highest-density stand classes ($>30\,000$ stems/ha).

Beyond the statistical performance, these results demonstrate that young, dense stands can be mapped wall-to-wall with sufficient accuracy to support real operational decisions. Forest managers can move from sparse sample-plot information to complete, georeferenced coverage of height and density, enabling better prioritization of which stands to treat first, how hard to thin, and where the risk of under- or over-thinning is highest. The method fits into existing planning workflows and can be replicated across thousands of hectares without a proportional increase in field work, turning tree-level detection into a scalable operational tool rather than a research prototype.

Metric	Height	Stem density
Correlation vs. field	0.96	0.93
Average bias	- 3%	- 4.7%
Mean absolute error (MAE)	~13%	~14%
Maximum tested density	–	~37 000 stems/ha
RTK-positioned plots	166	166
Number of geographical areas	16	16

Problem Description

Pre-commercial thinning stands represent one of the most challenging environments for automated tree detection. Stem densities frequently exceed 20,000–30,000 trees per hectare, with individual crowns measuring less than one meter in diameter and often merging into continuous canopy patches. This creates severe occlusion in both imagery and point cloud data, making reliable individual tree delineation fundamentally difficult. Spectral information from RGB sensors provides limited discrimination between closely spaced individuals, while point clouds struggle to resolve vertical structure when hundreds of small crowns occupy overlapping horizontal space.

Traditional field-based inventory methods achieve high local accuracy but face significant operational constraints. Manual measurements in dense young stands are physically demanding and time-consuming, with comprehensive coverage often requiring several hours per hectare. Sample plots are necessarily small—typically 25 to 50 m²—limiting their ability to capture spatial variability within heterogeneous stands. Subjectivity in borderline tree inclusion and crown classification introduces measurement variability, while the high cost of field work restricts the frequency and extent of assessments. Forest managers consequently make critical thinning decisions based on sparse, outdated, or spatially limited information.

Individual tree detection and model generalization in pre-commercial stands pose challenges beyond standard forest inventory. Training data must span extreme structural variation—from uniform planted stands to multi-layered natural regeneration—across different species, site conditions, and developmental stages. Models trained on managed stands in one region often fail when applied to structurally complex forests elsewhere, as spatial patterns and crown characteristics differ fundamentally. Robust generalization requires large annotated datasets capturing this variation, plus architectures capable of handling severe scale differences within single stands and distinguishing real stems from noise in overlapping canopy conditions.

Operational deployment demands more than high model accuracy. Systematic bias matters less than consistency: a model with 10% underestimation across all density classes may be operationally viable, while one with better average accuracy but variable bias is not. Georeferencing must be reliable enough for mechanized thinning equipment, data acquisition must be cost-effective at scale, and outputs must integrate into existing planning workflows. The challenge is delivering not just accurate detections, but a complete system that foresters can trust, verify, and use to make better thinning decisions across thousands of hectares.

Objective

This white paper evaluates tree detection accuracy for pre-commercial thinning stands using the Conifer Vision solution in northern Sweden. The focus is on young dense forests where reliable stem density estimates are critical for planning early silvicultural interventions.

Operational Impact

The outputs from the Conifer Vision system are delivered as high-resolution maps of stem density and mean height for each stand. In practice, planners and contractors use these maps to:

- select which stands should be prioritized for pre-commercial thinning in the next planning period
- identify pre-commercial thinning net area
- set realistic target densities and expected removal levels based on actual starting conditions
- optimize crew routing towards stands where interventions create the largest silvicultural and economic effect

Instead of extrapolating from a handful of small plots, users gain consistent, stand-wide information that can be directly imported into their existing GIS and planning tools. This reduces the time between data collection and action, and lowers the risk of mis-prioritization caused by incomplete or outdated field data.

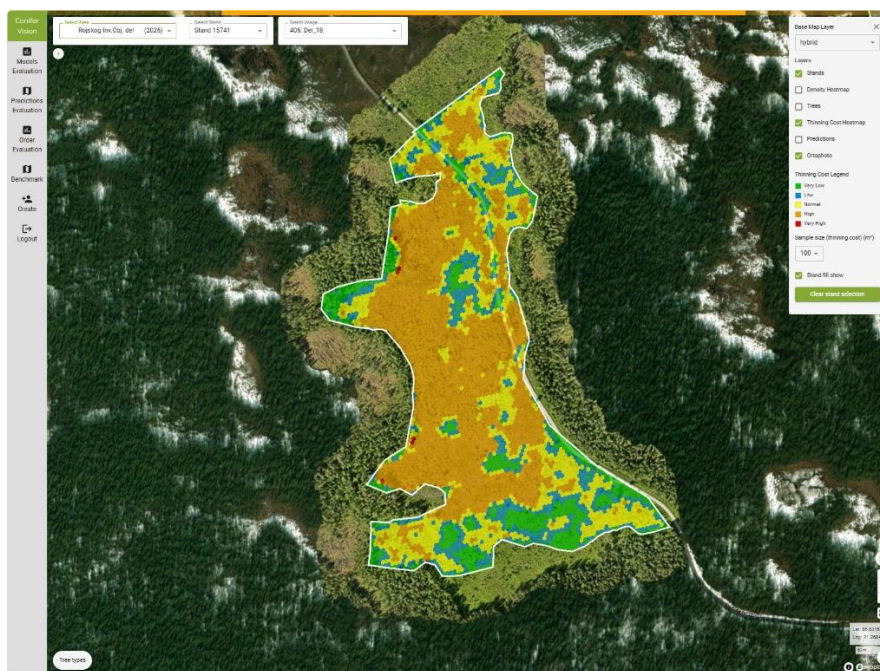


Figure 1 The map visualizes spatial variation in expected thinning cost within and between stands, enabling planners to target interventions.

Study Areas and Field Data

The study includes RTK-positioned circular test surfaces with a radius of 2.82 or 3.99 m, providing ground truth for stem density and mean height. In total, 166 test surfaces were measured, with 124 test surfaces distributed across 7 areas in Norrbotten county and 42 test surfaces distributed across 9 areas in Västerbotten county. All test surfaces represent pre-commercial thinning conditions with high stem densities, typically between about 9 000 and 37 000 stems per hectare.

The reference data are based on small, RTK-positioned circular plots, which provide high positional accuracy but relatively low total area coverage. Within each plot, tree measurements and classifications rely on manual, field-based interpretation, introducing some degree of subjectivity in, for example, borderline tree inclusion and crown delineation. The statistical comparisons in this study therefore rest on the assumption that these plots are representative of the surrounding stand conditions and that the field measurements themselves, while highly detailed, are not entirely free from measurement and observer error.

Methods

UAV imagery was acquired over all test areas using a high-resolution RGB camera flown at 70 m to capture dense overlap suitable for photogrammetric processing. The imagery was processed with structure-from-motion and dense matching workflows to generate detailed 3D point clouds and orthophotos of the pre-commercial thinning stands. The point clouds were rectified using RTK-measured ground and advanced data fusion, ensuring consistent georeferencing and accurate height representation across all sites.

A hybrid analysis pipeline was then applied, combining information from both the orthophoto and the 3D point cloud. Mathematical processing and dedicated AI models, specialized respectively in image analysis and point cloud analysis, were used together to identify individual trees, estimate their height, quantify stem density and determine species. By leveraging complementary data aspects from canopy structure and spectral information, the system produces consistent tree-level interpretations suitable for operational decision-making in pre-commercial thinning.

The AI models were trained on a large, annotated dataset of more than 220 000 individual pre-commercial tree objects, spanning a wide range of stand structures, species compositions and sensor conditions. This extensive training base supports robust generalization of crown delineation, height estimation and stem density prediction across both the managed Norrbotten stands and the more layered Västerbotten forests.

Robustness and system characteristics

Unlike approaches that rely primarily on generalized height models or grid-based density metrics, the Conifer Vision pipeline is designed to detect individual trees even in very dense, small-crowned stands. It combines high-resolution photogrammetric point clouds with specialized crown segmentation and filtering against RTK-accurate ground models, which stabilizes both height and density estimates when neighbouring crowns merge.

The architecture has been trained and validated on stands with strongly varying structure, from relatively homogeneous plantations to multi-layered natural regeneration. As a result, the system emphasizes consistency across sites as much as average accuracy: where bias occurs, it tends to be systematic rather than random, making it easier to handle operationally. This allows users to trust relative differences between stands and areas, even when local stand structure deviates from the training data.

Remote Sensing Analysis

The Conifer Vision analysis produced independent estimates of mean tree height and stem density for each test area based on high-resolution remote sensing data. For each of the 16 aggregated areas (7 in Norrbotten and 9 in Västerbotten), field-measured mean height and stem density were compared with the Conifer outputs to quantify systematic bias and variability. This setup allows evaluation of performance across a gradient of stand development, from approximately 1 m to almost 6 m in mean height.

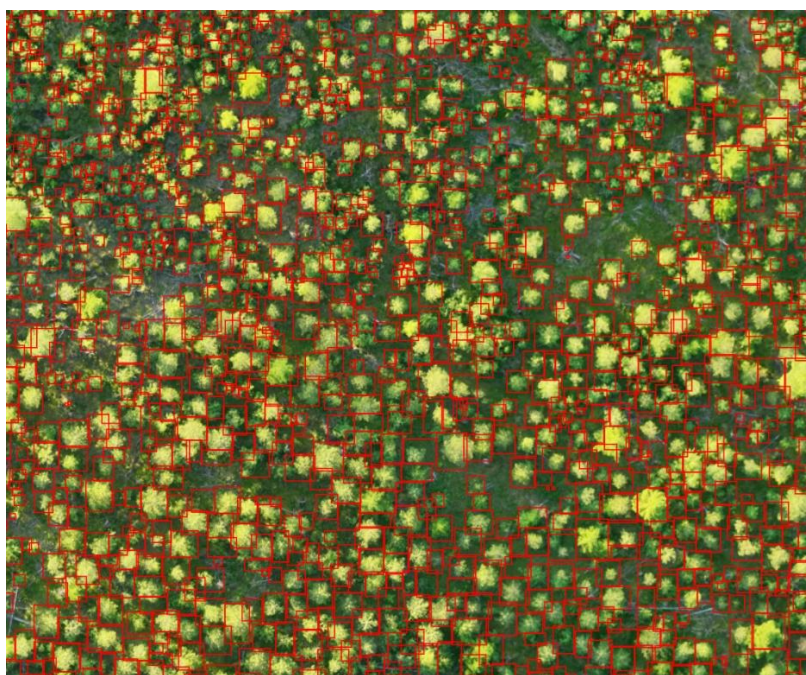
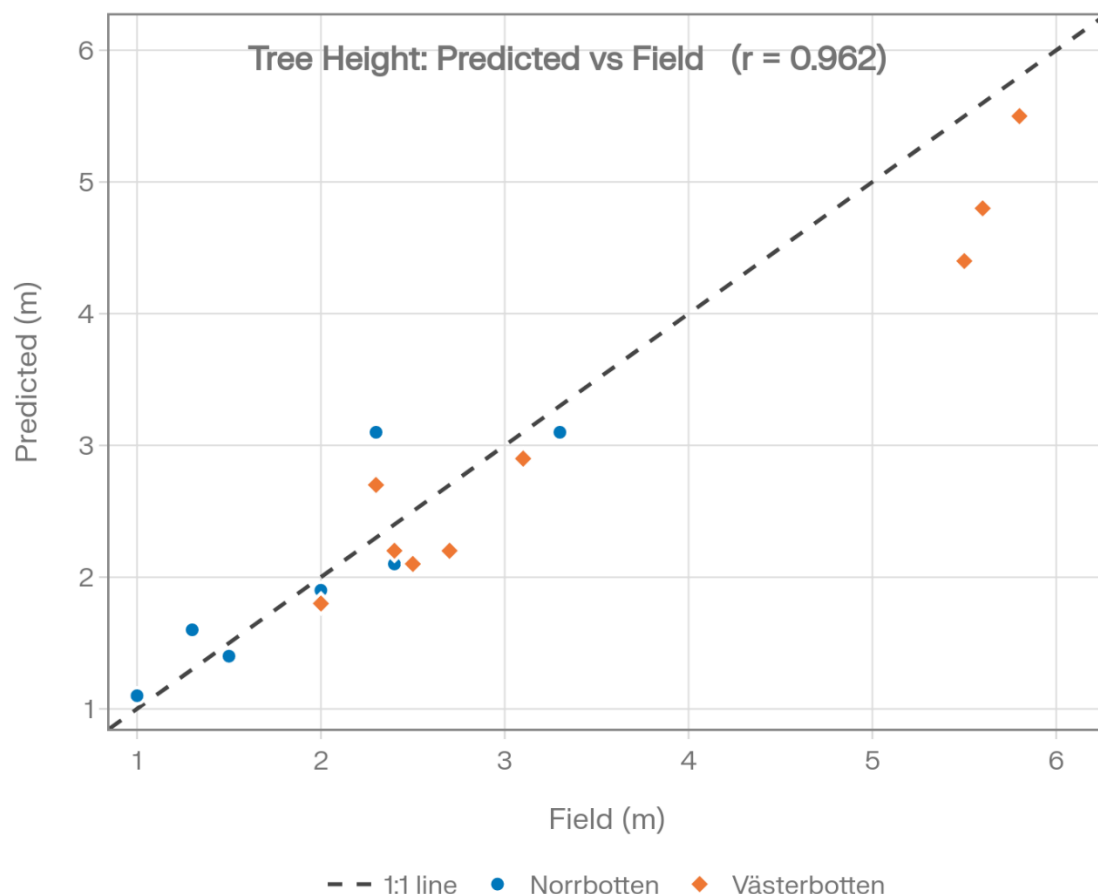


Figure 2 Detected stems overlaid on an orthophoto in a heterogenous stand. The system maintains consistent tree identification in both very dense patches and sparser edges, supporting fine-scale thinning planning.

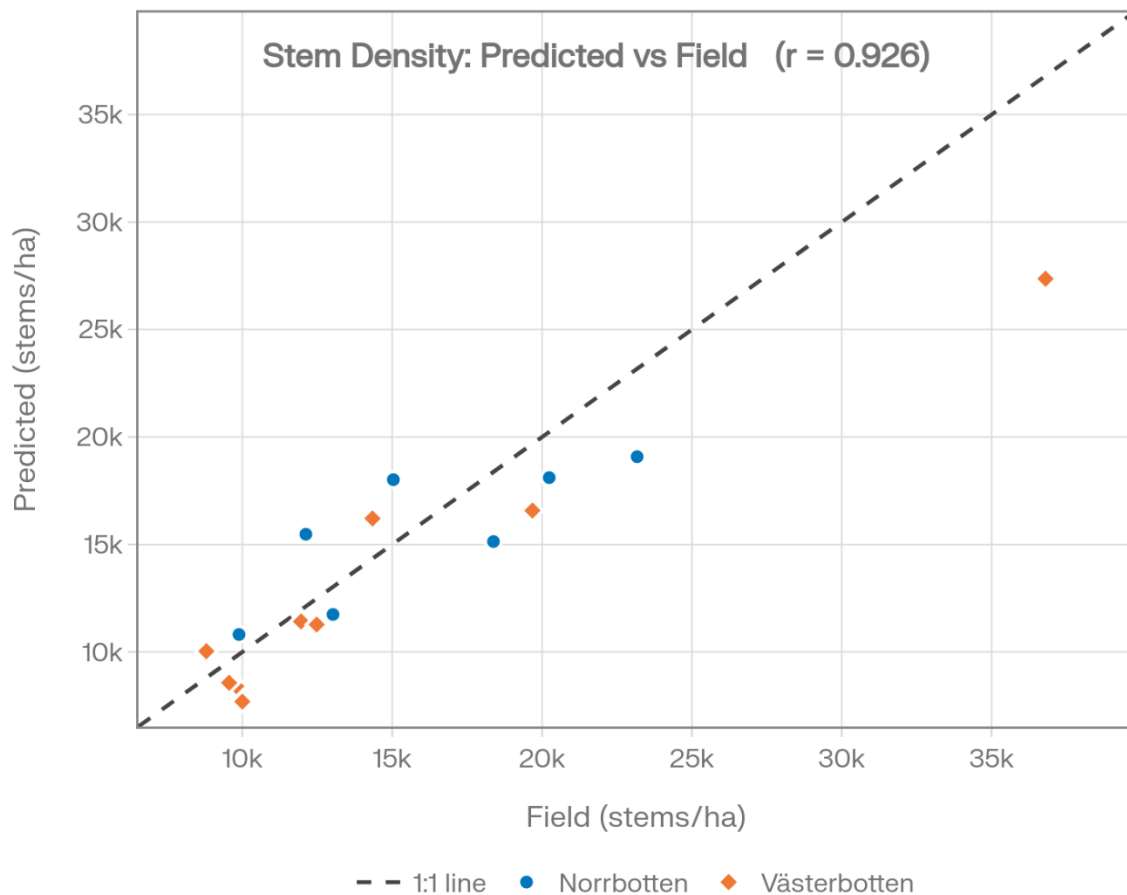
Height and Density Performance

Across all areas, the Conifer analysis reproduced mean stand height with small absolute deviations, typically within a few tenths of a meter of the field measurements. The correlation between field-measured and predicted mean height was very high ($r \approx 0.96$), indicating that the method closely tracks the height gradient between areas. On average, mean height was underestimated by roughly 3%, with a mean absolute error of about 13% of the field-measured height. Part of this systematic height underestimation can be explained by timing: field measurements were in several cases collected after the UAV campaigns, meaning that one growing season of height growth contributes to the observed bias.



For stem density, the Conifer estimates followed the field-measured patterns closely, with both over- and underestimation depending on stand structure and region. The correlation between field and predicted stem density was about 0.93, and the average density bias was modest at about -4.7%, meaning predicted densities were slightly lower than field measurements on average. The average absolute density error corresponded to roughly 14% of the field-measured density across the range of stands

— a strong result given the challenging conditions, and one that demonstrates the system's capacity for individual tree-level detection at scale in young dense forests.



Regional Patterns and Implications

The Norrbotten areas cover larger total areas and a wider density range than the Västerbotten areas, providing a robust test of performance in very dense early-thinning conditions. The Västerbotten areas were less maintained and contained more layered forests, with multi-storey structures and irregular spacing, illustrating how the method behaves in structurally complex young stands. Overall, the results indicate that remote sensing-based tree detection can provide operationally useful height and density information for pre-commercial thinning, but that additional training for very dense young stands is important to reduce underestimation of stem numbers in the highest density classes.

Conclusion

The validation results confirm that the system delivers accurate, individual tree-level detection in pre-commercial thinning stands under demanding boreal forest conditions. The high correlations for both height ($r \approx 0.96$) and stem density ($r \approx 0.93$), combined with low systematic bias, demonstrate that UAV-based remote sensing supported by hybrid AI analysis is a viable and scalable alternative to manual field inventory in young dense forests. Performance was consistent across both well-managed Norrbotten stands and the structurally more complex, layered forests of Västerbotten, underlining the robustness of the approach across varying silvicultural conditions. Continued expansion of the training dataset, with emphasis on extreme-density stands exceeding 30 000 stems/ha, is the most direct pathway to closing the remaining accuracy gap and enabling fully automated pre-commercial thinning planning at operational scale.

Taken together, the results indicate that AI-based tree detection in pre-commercial thinning stands is not only technically feasible, but mature enough to serve as a routine decision support input. The observed levels of correlation and bias are sufficient to replace a substantial share of traditional sample-plot inventory with remote sensing, without sacrificing the precision needed to guide treatment intensity and target density. Because the data collection is UAV-based and the processing workflow is highly automated, the same method can be rolled out across large forest holdings with consistent methodology and comparable results between regions. This enables a more systematic, data-driven governance of pre-commercial thinning, where resources are directed towards the stands with the highest expected impact on growth, stand quality, and future harvesting flows.

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