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"Towards multi-functional agro-ecosystems
promoting climate resilient futures"

Measuring reforestation success with very-high-resolution satellite imagery

Tobias Hellmundt[1], Fabian Wölk[2]

[1] *University of Göttingen, Dept. of Economics, Germany*
[2] *University of Göttingen, Inst. of Computer Science, Germany*

Abstract

Forest landscape restoration is increasingly mobilised as a multi-functional strategy for climate-resilient land-use systems, simultaneously targeting carbon sequestration, soil and watershed protection, biodiversity recovery, and rural livelihoods. Yet many large-scale reforestation programmes fall short of their ecological objectives, and credible plot-level monitoring of tree establishment and survival remains a critical bottleneck. Without it, programmes risk being judged on planting effort alone, leaving establishment failures invisible and learning across sites impossible. A core obstacle is a resolution–coverage gap in satellite imagery: free, high-frequency global imagery is typically available only at moderate resolutions (10–30 m), too coarse to detect small or recently planted trees, while sub-meter very-high-resolution (VHR) imagery is costly and unevenly available. We introduce a two-stage machine learning framework that bridges this gap. A U-Net first learns to segment individual tree canopies on a limited sample of sub-meter VHR imagery; a second U-Net then transfers this signal to widely available 5 m Planet NICFI basemaps to produce wall-to-wall, plot-level fractional tree-cover estimates. The pipeline achieves a mean IoU score of 82 % on canopy segmentation and explains 83 % of the variance in fractional cover at 5 m. Benchmarked against the vegetation-index trend approach commonly used in restoration evaluation, our model captures 85 % of true tree pixels versus only 34 % for the vegetation-index trend baseline, with comparable false-positive rates. We apply the framework to Madagascar's PLAE afforestation programme (Phase III, 2014–2019), which planted roughly 7,000 ha across more than 5,800 smallholder plots in the Boeny, Betsiboka, and DIANA regions. Combining our tree-cover maps with a covariate-based matching design that controls for terrain, soil characteristics, accessibility, and pre-existing forest cover, we find moderate gains on planted plots: 5–8 years after planting, tree cover is 4.7–12.5 percentage points higher than on matched control sites, though a majority of plots remain largely treeless.

By enabling scalable, data-efficient plot-level monitoring, this approach delivers an empirical foundation needed to design, verify, and adaptively manage multi-functional restoration efforts in data-limited settings.

Keywords: Deep learning, impact evaluation, Madagascar, reforestation monitoring, remote sensing

Contact Address: Tobias Hellmundt, University of Göttingen, Dept. of Economics, Göttingen, Germany, e-mail: tobias.hellmundt@uni-goettingen.de