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National-scale datasets underestimate vegetation recovery in Australian human-induced native forest regeneration carbon sequestration projects

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Limiting global warming below 2 °C requires nature-based climate solutions, which are expected to supply more than a third of cost-effective climate mitigation by 2030[1,2], while prioritizing avoiding fossil fuel emissions. Regenerating native forests under the Australian Government's Australian Carbon Credit Unit (ACCU) program is delivering large-scale carbon storage across approximately 3.4 million hectares. Projects using the human-induced regeneration (HIR) method[3] aim to restore native forests through improved land management, generating ACCUs that underpin both legislated emissions reduction and voluntary decarbonization targets. Scientific rigor must underpin the integrity of the ACCU program. Constructive critiques of carbon crediting programs allow refinement over time, strengthening climate action[4]. However, inadequate analyses that lack necessary analytical rigor can undermine investment decisions and diminish real outcomes when they impact critical policy decisions[5].

Macintosh et al.[6] contend that HIR activities are having limited influence on changes in woody vegetation cover in Australia. Macintosh et al.[6] analyzed the National Forest and Sparse Woody Vegetation Dataset (NFSWVD[7]) to compare vegetation trends between credited HIR areas and adjacent comparison areas. Others[8] have used a similar process and approach to investigate HIR project performance using the publicly available Woody Cover Fraction (WCF[9]) data set. However, these national-scale datasets (NFSWVD & WCF) are used without valid empirical support that the data were fit for purpose, a standard scientific convention. Here, we provide evidence that their assessment relies on two untested assumptions:

1. that publicly available, national-scale datasets can accurately detect and quantify vegetation cover at the scale of individual projects, and
2. that adjacent comparison areas represent valid experimental controls.

We present evidence that contradicts the conclusions of Macintosh et al.[6]. Our analysis, using high-quality reference data collected on HIR projects as standard practice, reveals that the national datasets (NFSWVD & WCF) are not fit for this type of assessment, as they significantly underestimate regeneration. We also demonstrate that the experimental design of Macintosh et al.[6] has fundamental design problems that undermine their findings.

NFSWVD is not fit-for-purpose as a standalone tool to examine HIR project performance

We assessed the accuracy of publicly available national datasets using a reference dataset of high-resolution airborne lidar obtained from representative HIR project sites in the Queensland, New South Wales and Western Australia rangelands (*Methods*). These direct comparisons reveal systematic underestimation of vegetation condition by the national data sets relative to the lidar reference data.

NFSWVD detected 40% less sparse woody vegetation than reference lidar (Fig. 1a), precisely the early stage regeneration that characterizes successful HIR interventions. Similarly, WCF did not identify most vegetation below 20% canopy cover, essentially missing early-stage regeneration (Fig. 1b, c). Overall, WCF was moderately correlated with reference lidar ($R^2 = 0.6$), particularly at high canopy cover, however the magnitude of relative errors (126% relative root mean square deviation; relRMSD) indicates substantial disagreement overall.

Furthermore, NFSWVD predicted sparse woody vegetation in different locations than the reference lidar data (Table 1). NFSWVD was unable to detect four out of five (4/5) validation plots with predominantly sparse vegetation (omission) and only one in four (1/4) areas mapped by NFSWVD as sparsely wooded was classified correctly (commission). Commission errors in sparse woody vegetation predominantly occur by misclassifying forest as sparse woody vegetation, rather than by overestimating vegetation where there is none. More than half of the areas classified by NFSWVD as bare ground contained measurable tree cover above Australia's 2-meter forest height threshold (Fig. 1a; Table 1). Finally, the overall accuracy is only 56.4 %, well below the regulated 85% accuracy threshold required for HIR project monitoring[10].

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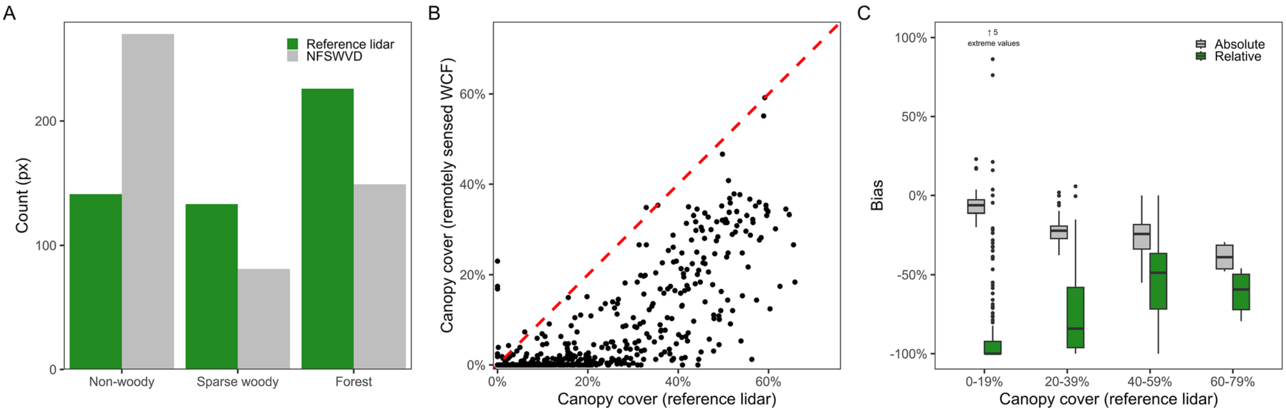

Fig. 1 | Canopy cover characterization and accuracy assessment. **A** Comparison of class frequencies for NFSWVD against reference lidar. **B** Comparison of WCF canopy cover against reference lidar. The dashed 1:1 line indicates perfect agreement. **C** Absolute and relative bias of WCF by canopy cover.

Table 1 | Confusion matrix comparing classification results between NFSWVD (rows) and reference lidar dataset (columns) for 500 validation points, with associated omission and commission errors and overall accuracy (OA)

		Reference lidar				
		Non-woody	Sparse woody	Forest	Total	Commission
NFSWVD	Non-woody	131	97	42	270	51.5%
	Sparse woody	4	22	55	81	72.8%
	Forest	6	14	129	149	13.4%
	Total	141	133	226	500	
	Omission	7.1%	83.5%	42.9%		OA: 56.4%

In summary, the publicly available datasets were not seen to be able to detect regenerating woody vegetation with canopy cover <20% (NFSWVD and WCF), and commonly misrepresented forest (>20%) cover as sparse woody vegetation (NFSWVD) when compared to lidar derived measurements. These findings invalidate the assumptions of Macintosh et al.[6] that the national-scale datasets are appropriate for project level assessment of vegetation cover and change over time, and support a previous ruling that such data are not appropriate as standalone tools for the assessment of HIR projects[11]. While the NFSWVD is used and calibrated for national-scale inventory reporting, the Australian Government recognizes this product is unsuitable for the detection of early-stage regeneration at a local site scale.

Issues with experimental design, analysis and presentation of data

Macintosh et al.[6] compared NFSWVD forest cover trends within credited areas of HIR projects and surrounding comparison areas extending up to three kilometers from the project perimeters. However, using fixed-width buffers resulted in dramatically mismatched comparison areas, ranging from 4% to 926% of the credited areas size (Supplementary Discussion).

Robust impact evaluation requires the careful section of control sites, matched in character (initial vegetation condition, soil properties, hydrological regimes, fire history, historical and current land management practices[12]). The analysis of Macintosh et al.[6], conducted within a region of high environmental variability[13], is inappropriately designed because it assumes without any empirical supporting evidence that geographic proximity adequately controls for these often confounding factors. The use of poorly matched comparison areas (differing in size and character) violates basic principles of experimental design and introduces substantial bias. Because these comparison areas may contain land unsuitable for forest growth, already heavily forested, and/or ineligible for undertaking HIR activities, the direction of bias cannot be determined. Macintosh et al.[6] obscured this variability by presenting their findings without confidence intervals or uncertainties (their Figure 3) but it is evident when the data are presented differently (Fig. 2).

Finally, the statistical analysis treats year-to-year changes in NFSWVD in projects and adjacent areas as independent samples. Given the variable registration dates of the project cohort, the dataset is artificially inflated and heavily weighted toward early project stages, with very few observations of projects over ten years old. This unbalanced dataset likely underestimates the effect of HIR activities when vegetation change is expected to be gradual and non-linear over time. The absence of a statistically detectable effect, regardless of measurement approach, reflects compounding methodological limitations rather than actual project performance.

A "fit-for-purpose" approach

Best practice in HIR project monitoring requires substantial, high-quality evidence to verify project performance[14]. Project proponents must demonstrate regeneration potential, including proof of young tree cohorts, implementation of management changes, and vegetation maps validated against independent reference data[10]. A high degree of confidence in HIR projects is essential for the ACCU program, given its role in Australia's national mitigation strategy. Even with continued improvements in national products, project-level verification will remain essential given Australia's complex rangeland ecosystems.

While national-scale carbon monitoring presents substantial challenges, advances in model-data fusion can improve assessment of vegetation change over large areas[15]. These products remain important for tracking broad changes in landscapes and land use, and could be enhanced through integration with project-level data. We suggest that the data collected for HIR project monitoring be used as a key input to the development of Australia's national scale forest monitoring system. We have already engaged in discussion with the Australian Government in this regard.

Effective climate action depends on transparency and scientific rigor, and engaging with critique and commentary. The analysis of Macintosh et al.[6] lacks the rigor needed for the reliable assessment of HIR project or overall program performance. Future policy development, including program review or new method development, must recognize the value and limitations of national monitoring systems and be cautious when considering the adequacy of such analyses as mentioned here. Systematic underestimation of regenerating vegetation, based on inappropriate data sets and questionable experimental design can easily lead to incorrect conclusions about project effectiveness and discourage investment in nature-based climate solutions precisely when their scaling up is most crucial.

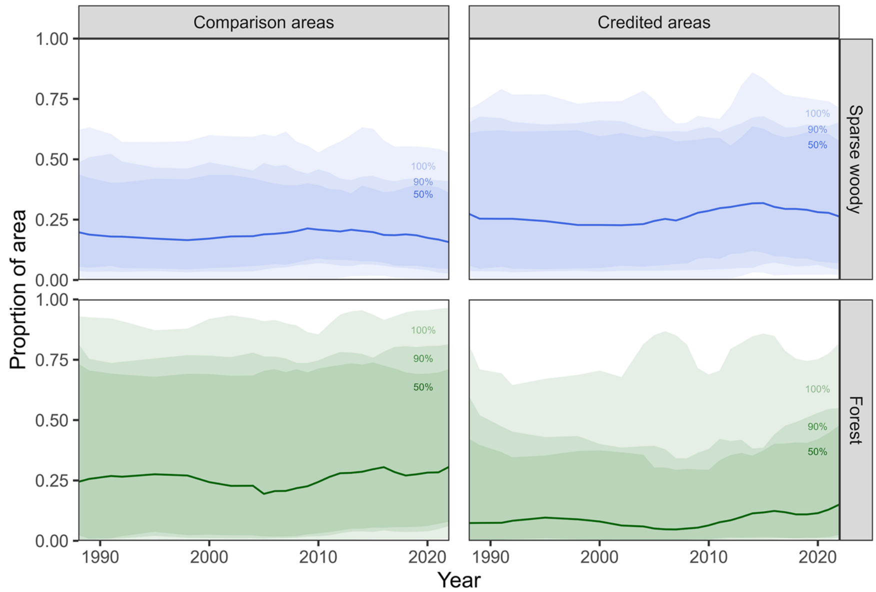

Fig. 2 | Median trends (solid lines) and quantiles (50%, 90% and 100%) of NFSWVD forest and sparse woody vegetation proportions within the credited and comparison. Reproduced with data from Macintosh et al.[6].

Methods

We acquired high-resolution airborne laser scanning (ALS) data across five study sites, totaling approximately 59,000 hectares (Supplementary Fig. 2). Fixed-wing aircraft surveys followed standard forest measurement protocols. Data collection used real-time kinematic or post-processed kinematic correction to achieve high relative positional accuracy with absolute precision within ±1.5 m. Point cloud density exceeded 10 points/m² to ensure reliable canopy characterization. We generated canopy height maps and used a two-stage height thresholding process to define a binary crown map (Supplementary Methods).

For comparison with satellite products, we transformed the binary crown maps and averaged the high-resolution crowns to 25 m resolution to match NFSWVD and WCF coordinate systems and grids. The analyzed lidar surveys were collected in 2021 and 2022 and compared against contemporary national-scale estimates from NFSWVD (ver 7.0) and WCF. We randomly selected 100 sample locations from each ALS survey (500 total) to ensure unbiased representation across varying survey sizes. For each location, we extracted 75 × 75 m samples from both datasets, corresponding to 3 × 3 windows in the satellite products. While these samples represented the same approximate geographic locations, the areas analyzed differ slightly between NFSWVD and WCF comparisons due to CRS transformations. This sampling approach, combined with the 3 × 3 window size, helped minimize the impact of both geolocation errors and CRS transformation effects. We only included samples where all nine satellite pixels fell completely within the lidar coverage area.

Data availability

Our analytical dataset, comprising resampled forest classification values (25 m and 75 m resolution) used for all statistical comparisons, is available in deidentified CSV format at https://doi.org/10.6084/m9.figshare.29287811.v1 and https://doi.org/10.6084/m9.figshare.2519978. Raw lidar surveys cannot be shared due to privacy protections for private landowners whose properties were surveyed for regulatory compliance.

Code availability

The code used to create the tables and figures is available from the corresponding author upon reasonable request.

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Author contributions
T.M. conceived the study, designed the research, and wrote the initial manuscript. A.O. conducted the data analysis. T.M. A.O., K.C. and C.W. contributed to the revision of the manuscript and approved the final version for submission.

Competing interests
The authors T.M., A.O., K.C. and C.W. declare no competing non-financial interests. The authors T.M., A.O., K.C. and C.W. declare the following competing financial interest—the authors receive financial remuneration for administering carbon farming projects and monitoring their performance.

Additional information
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