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Title: National-scale datasets systematically underestimate vegetation recovery in Australian carbon farming 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 prioritising avoiding fossil fuel emissions. Regenerating native forests under the Australian Government's Australian Carbon Credit Unit (ACCU) program are 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 decarbonisation targets. Scientific rigour must underpin the integrity of the ACCU program. Constructive critiques of carbon crediting programs allow refinement over time, strengthening climate action[4]. However, flawed analyses that lack necessary analytical rigour can undermine investment decisions and diminish real outcomes when they impact critical policy decisions[5].

Macintosh et al. (2024[6]; hereafter Macintosh) contend that HIR activities are having limited influence on changes in woody vegetation cover in Australia. Macintosh analysed the National Forest and Sparse Woody Vegetation Dataset (NFSWVD[7]) and, elsewhere[8], Woody Cover Fraction (WCF[9]) to compare vegetation trends between credited HIR areas and adjacent comparison areas. However, Macintosh provides no valid empirical support to validate the data sets they applied 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 applied high quality reference data, collected on HIR projects as standard practice, as empirical evidence that the national-scale datasets (NFSWVD & WCF) used by Macintosh systematically underestimate regeneration success on HIR projects in the Australian rangelands, and are therefore not fit for purpose as used by Macintosh. We also demonstrate that Macintosh' s experimental design has significant fundamental design failures that undermines 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 (Figure 1a), precisely the early stage regeneration that characterises successful HIR interventions. Similarly, WCF failed to identify most vegetation below 20 % canopy cover, essentially missing early-stage regeneration (Figure 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 failed 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 areas classified by NFSWVD as bare ground contained measurable tree cover above Australia's 2-meter forest height threshold (Figure 1a; Table 1). Finally, the overall accuracy is only 56.4 %, well below the regulated 85% accuracy threshold required for HIR project monitoring[10].

In summary, the publicly available datasets failed 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 MacIntosh's assumption 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 recognises 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 compared NFSWVD forest cover trends within credited areas of HIR projects and surrounding comparison areas extending up to three kilometres 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]). Macintosh's analysis, conducted within a region of high environmental variability[13], is flawed because it assumes 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 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 (Figure 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 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 rigour, and engaging with critique and commentary. Macintosh's analysis 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.

Methods

We acquired high-resolution airborne laser scanning (ALS) data across five study sites, totalling approximately 59,000 hectares (*Supplementary Figure 2*). Fixed-wing aircraft surveys followed standard forest measurement protocols. Data collection used real-time kinematic (RTK) or postprocessed kinematic (PPK) correction to achieve high relative positional accuracy with absolute precision within ±1.5m. Point cloud density exceeded 10 points/m² to ensure reliable canopy characterization. We generated canopy height maps and used a two state 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 25m resolution to match NFSWVD and WCF coordinate systems and grids. The analysed 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 x 75 m samples from both datasets, corresponding to 3x3 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 3x3 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.

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Author Contributions

T.M. conceived the study, designed the research, and wrote the manuscript. A.O. conducted the data analysis. All authors contributed to the revision of the manuscript and approved the final version for submission.

Data availability statement

The source data for all figures and tables in the current study are available in tabular comma-separated values (CSV) format at https://doi.org/10.6084/m9.figshare.29287811.v1 and https://doi.org/10.6084/m9.figshare.2519978.

Code Availability Statement

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

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Tables

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).

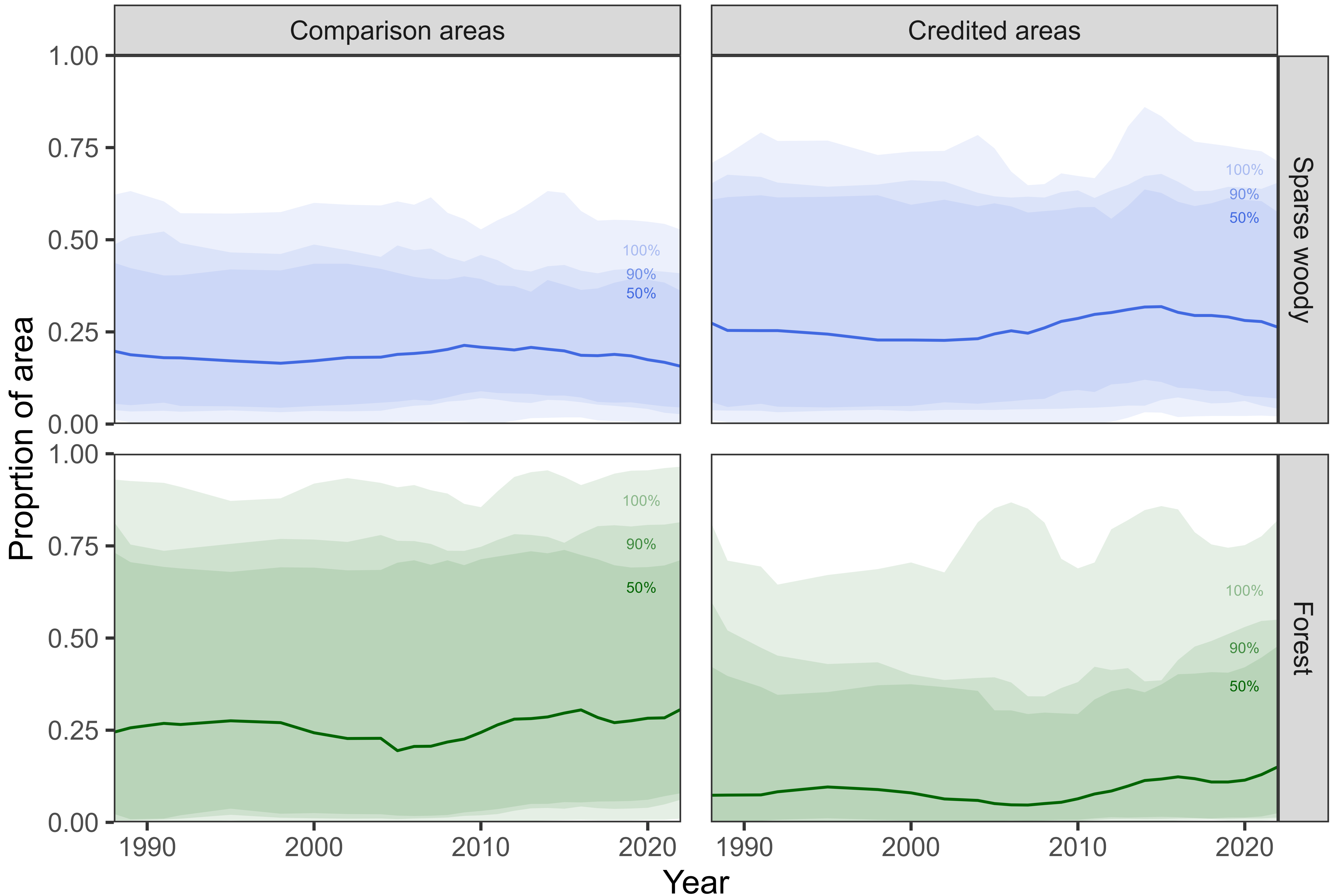
		Reference lidar				
		Non-woody	Sparse woody	Forest	Total	Commission
NFSWVD	Non-woody	131	97	42	270	51.5%
	Sparse woody	4	22	55	81	72.8%
	Forest	6	14	129	149	13.4%
	Total	141	133	226	500	
	Omission	7.1%	83.5%	42.9%		OA: 56.4%

Figure captions

Figure 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.

Figure 2. Median trends (solid lines) and quantiles (50%, 90% and 100%) of NFSWVD forest and sparse woody vegetation proportions within credited and comparison. Reproduced with data from Macintosh et al (2024).

A
Count (px)
200
100
0
Reference lidar
NFSWVD
Non-woody
Sparse woody
Forest
B
Canopy cover (remotely sensed WCF)
60%
40%
20%
0%
20%
40%
60%
Canopy cover (reference lidar)
C
Bias
100%
50%
0%
-50%
-100%
↑ 5
extreme values
Absolute
Relative
0-19%
20-39%
40-59%
60-79%
Canopy cover (reference lidar)



Comparison areas
Credited areas
Sparse woody
Forest
1.00
0.75
0.50
0.25
0.00
100%
90%
50%
1990
2000
2010
2020
Proprtion of area
Year