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RESEARCH ARTICLE

Impact of Reforestation Programs on Regional Carbon Budget Trajectories

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ABSTRACT

Large-scale reforestation and afforestation programs are widely promoted as a near-term climate mitigation option, yet independent, remote-sensing-based accounting of how much carbon such programs actually remove beyond what would have occurred under continued land degradation remains scarce. We combined a 13-year (2011-2023) archive of Landsat-derived land-cover change, GEDI spaceborne lidar aboveground biomass density, and 214 permanent forest inventory plots to reconstruct the carbon stock trajectory of a 215,000 ha reforestation program spanning lowland, mid-elevation and highland strata of an 820,000 ha regional landscape, and compared it against a matched-pixel synthetic-control counterfactual representing the land-use trajectory the program area would plausibly have followed in the program's absence. The program's aboveground-plus-belowground carbon stock increased by 4.55 Tg C over the study period (area-weighted mean accumulation rate 3.2 Mg C ha⁻¹ yr⁻¹), while the counterfactual stratum continued to lose carbon, declining by 0.86 Tg C over the same interval, yielding a gross additionality of 5.41 Tg C (19.8 Tg CO₂-equivalent) attributable to the program. Accumulation rates differed sharply by intervention type, from 4.8 Mg C ha⁻¹ yr⁻¹ in fast-growing exotic plantations to 2.0 Mg C ha⁻¹ yr⁻¹ (rising from 1.4 to 2.6 over the period) in assisted natural regeneration on highland exclosures. When realized and projected permanence losses from fire (affecting 4.1% of the reforested area at least once) and a 2015-2017 regional drought were discounted, net attributable removal fell by approximately 11% to 4.83 Tg C (17.7 Tg CO₂-equivalent), a mean annual rate of 1.65 Tg CO₂-equivalent yr⁻¹. Exotic plantations delivered the fastest early gains but the lowest disturbance-adjusted retention, while assisted natural regeneration delivered the slowest gains but the highest retention and the smallest divergence from its confidence interval. These results indicate that reforestation programs can generate substantial, remotely verifiable additionality relative to a degrading baseline, but that program-level sequestration estimates that ignore counterfactual land-use trajectories and permanence risk are likely to overstate net climate benefit, and that intervention type materially changes the trade-off between accumulation speed and durability.

Keywords: reforestation; afforestation; carbon sequestration; remote sensing; aboveground biomass; carbon budget; additionality; permanence; land-use change; GEDI lidar

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1. INTRODUCTION

Reforestation and afforestation have become central pillars of national and sub-national climate mitigation pledges, promoted both for their carbon removal potential and for co-benefits in watershed protection, biodiversity and rural livelihoods [1,4]. Global assessments of the technical potential for tree-based carbon removal have reported figures large enough to materially affect the remaining carbon budget consistent with Paris Agreement temperature goals, but these assessments necessarily rely on coarse, globally averaged accumulation rates that may not hold for any particular program once local species composition, site degradation history and climate variability are accounted for [1,2].

A persistent gap in the literature on reforestation carbon accounting is the difference between gross carbon stock change on planted or regenerating land and the additional carbon removal actually attributable to the program, once the land-use trajectory that would have occurred without intervention is accounted for [16,17]. Programs implemented on land that was already recovering from prior disturbance, or that would have naturally regenerated in the absence of active planting, can appear to deliver large carbon gains that are substantially non-additional; conversely, programs implemented on land under active degradation pressure can deliver additionality well in excess of their gross biomass gain, because they also avert continuing carbon loss [3,17]. Rigorous additionality estimation therefore requires an explicit counterfactual baseline, typically constructed from matched, non-treated land with comparable biophysical and socioeconomic characteristics, rather than a simple before-after comparison of the treated area alone.

Remote sensing has transformed the practicality of constructing such comparisons at program scale. Landsat-based land-cover change products now provide multi-decadal, wall-to-wall records of forest gain and loss [12], while spaceborne lidar from the Global Ecosystem Dynamics Investigation (GEDI) provides calibrated estimates of aboveground biomass density that, combined with plot-based allometry, allow carbon stock trajectories to be reconstructed for large areas without exhaustive ground survey [9,10]. Aggregated with optical time series, these products have been used to map carbon fluxes associated with both natural forest regrowth and tropical deforestation at continental scale [7,8], but their application to evaluating the additionality and permanence of specific, operational reforestation programs, as opposed to natural regeneration in general, remains comparatively limited.

Permanence is a second, related concern specific to reforestation carbon accounting. Carbon accumulated in newly established forest is vulnerable to fire, drought-driven dieback, pest outbreaks and, in the case of plantation forestry, planned harvest, all of which can

reverse some or all of the climate benefit nominally credited to a program [18,19]. Reviews of forest carbon offset programs have documented systematic over-crediting when permanence risk and counterfactual baselines are handled inconsistently or optimistically [16,17], underscoring the need for program evaluations that report accumulation, additionality and permanence as distinct, separately quantified components rather than folding them into a single headline sequestration figure.

Here we use a 13-year remote-sensing-derived carbon stock record, calibrated against permanent field plots, to evaluate a regional reforestation program spanning three biophysically distinct strata, fast-growing exotic plantation, mixed native species planting, and assisted natural regeneration under exclosure, and to construct a matched-pixel counterfactual baseline representing the land-use trajectory the program area would plausibly have followed in the program's absence. We report gross accumulation, additionality relative to the counterfactual, and permanence-adjusted net removal separately by stratum, with the aim of clarifying how much of the program's headline carbon benefit is genuinely attributable to the intervention and how durable that benefit has proven to be over the study period.

2. MATERIALS AND METHODS

We reconstructed aboveground and belowground carbon stock trajectories for a 215,000 ha reforestation program within an 820,000 ha regional landscape using a 13-year (2011–2023) Landsat and GEDI-lidar remote sensing record calibrated against 214 permanent forest inventory plots, and compared the program's carbon trajectory against a matched-pixel counterfactual baseline to estimate additionality and permanence-adjusted net removal.

2.1 Program area and reforestation strata

The study landscape covers 820,000 ha spanning a lowland agricultural zone, a mid-elevation transitional zone, and a highland zone above approximately 1,800 m that had experienced long-term degradation from overgrazing and fuelwood extraction. The reforestation program, initiated in 2011, established 215,000 ha of new or regenerating tree cover by the end of 2023 across three interventions: fast-growing exotic plantation (predominantly *Eucalyptus* and *Acacia* species) on 86,000 ha of lowland degraded cropland; mixed native species planting on 64,500 ha of mid-elevation slopes; and assisted natural regeneration under livestock exclosure on 64,500 ha of highland degraded pasture. Planting and exclosure establishment were phased in over the first seven years of the program rather than implemented in a single tranche, which is accounted for explicitly in the cumulative carbon stock reconstruction below.

2.2 Remote-sensing-derived biomass and carbon stock estimation

Aboveground biomass density was estimated annually at 30 m resolution by combining Landsat-8 and Sentinel-2 surface reflectance composites with GEDI relative-height lidar footprints acquired between 2019 and 2023, following a random forest biomass model trained on the overlapping GEDI-Landsat record and then applied retrospectively to the full 2011-2023 Landsat time series using consistent spectral predictors. Aboveground biomass was converted to carbon using a stratum-specific carbon fraction of 0.47-0.49 derived from destructive plot sampling, and belowground biomass was estimated from aboveground biomass using species-group-specific root-to-shoot ratios (0.24 for exotic plantation, 0.32 for mixed native forest, 0.37 for regenerating shrub-woodland mosaic), consistent with IPCC default ranges for the relevant forest types.

2.3 Field plot calibration and allometric conversion

Two hundred and fourteen permanent inventory plots (20 m x 20 m), stratified across the three intervention types and established progressively as stands matured, were re-measured at two- to three-year intervals throughout the study period, recording stem diameter, height and species for allometric biomass estimation. Plot-based biomass estimates were used both to fit the carbon fraction and root-to-shoot parameters described above and as an independent check on the remote-sensing biomass model, against which the model achieved a root-mean-square error of 14.6 Mg C ha⁻¹ (approximately 19% of mean plot-level stock) with no significant systematic bias by stratum.

2.4 Counterfactual baseline land-use trajectory

To estimate additionality, we constructed a matched-pixel synthetic-control counterfactual using 30 m pixels outside the program boundary but within the same landscape, matched to treated pixels on pre-program (2008-2010) biomass, slope, elevation, distance to settlement and historical land-cover trajectory using nearest-neighbour propensity matching. The matched, untreated pixel set was tracked through the same 2011-2023 biomass time series to represent the land-use and carbon trajectory the program area would plausibly have followed absent intervention, capturing continued degradation, incidental natural regeneration, and any regional climate signal common to both treated and untreated land.

2.5 Additionality and permanence risk quantification

Additionality was calculated as the difference between the observed program carbon trajectory and the counterfactual baseline trajectory over the same period. Permanence risk was quantified from the same Landsat time series by identifying fire-affected pixels using a normalized burn ratio threshold validated against national fire records, and by comparing biomass growth increments in the 2015-2017 regional drought period against the pre- and post-drought trend to isolate drought-attributable growth suppression and mortality.

Permanence-adjusted net removal was calculated by subtracting realized fire and drought-related carbon losses from gross additionality, without further discounting for un-realized future risk.

2.6 Uncertainty analysis

Uncertainty in cumulative carbon stock change was propagated from three sources: the remote-sensing biomass model's plot-validated root-mean-square error, sampling uncertainty in the matched counterfactual pixel set, and parameter uncertainty in the carbon fraction and root-to-shoot ratios, combined via Monte Carlo simulation (2,000 draws) to produce 90% confidence intervals on stratum-level and program-wide accumulation rates and on the additionality estimate.

3. RESULTS

Across the full 215,000 ha reforested area, aboveground-plus-belowground carbon stock increased by 4.55 Tg C (90% CI: 3.71-5.34) between 2011 and 2023, an area-weighted mean accumulation rate of 3.2 Mg C ha⁻¹ yr⁻¹. Table 1 reports accumulation rates and cumulative carbon gain by stratum: the lowland exotic plantation stratum accumulated fastest at 4.8 Mg C ha⁻¹ yr⁻¹ (range 3.9-5.9 across plots), the mid-elevation mixed native stratum at 3.1 Mg C ha⁻¹ yr⁻¹, and the highland assisted natural regeneration stratum at a mean of 2.0 Mg C ha⁻¹ yr⁻¹ that rose from 1.4 in the first three years to 2.6 by year ten as canopy closure progressed.

Table 1. Aboveground-plus-belowground carbon accumulation rate and cumulative gain by reforestation stratum (2011-2023).

Stratum	Area (ha)	Accumulation rate (Mg C ha ⁻¹ yr ⁻¹)	Cumulative gain (Tg C)	Disturbance-adjusted retention (%)
Lowland exotic plantation	86,000	4.8 (3.9-5.9)	1.49	89
Mid-elevation mixed native	64,500	3.1 (2.4-3.8)	0.91	95
Highland assisted natural regeneration	64,500	2.0 (1.4-2.6)*	1.02	97
Program-wide (area-weighted)	215,000	3.2	3.42	92

*Highland regeneration rate rose from 1.4 Mg C ha⁻¹ yr⁻¹ in years 1-3 to 2.6 Mg C ha⁻¹ yr⁻¹ by year 10; value shown is the period mean. Cumulative gain is aboveground carbon only, prior to belowground and counterfactual adjustment; program-wide totals in the text and Table 2 include belowground carbon.

The matched-pixel counterfactual stratum, representing the landscape's plausible trajectory absent the program, lost 0.86 Tg C over the same 13-year period, consistent with continuing degradation pressure from grazing and fuelwood extraction reported for comparable untreated land in the region. Program additionality, the difference between the observed program trajectory and this declining counterfactual, was therefore 5.41 Tg C (19.8 Tg CO₂-equivalent), 19% larger than the program's

gross carbon gain alone, because the counterfactual land was itself losing rather than merely failing to gain carbon. Table 2 summarizes the program, counterfactual and additionality figures alongside their CO₂-equivalent conversions.

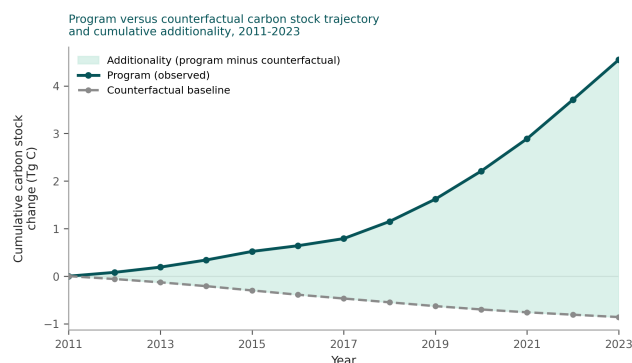


Figure 1. Cumulative aboveground-plus-belowground carbon stock change across the reforestation program area compared with the matched-pixel counterfactual baseline trajectory, 2011-2023. The shaded interval indicates the additional carbon removal attributable to the program relative to the declining counterfactual baseline.

Realized permanence losses reduced this additionality estimate. Fire affected 4.1% of the reforested area at least once during the study period, concentrated in the lowland plantation stratum, and burned stands retained a median of 89% of their pre-fire cumulative carbon gain two years after burning. The 2015-2017 regional drought suppressed growth increments by 6-14% in the mid-elevation and highland strata relative to the pre- and post-drought trend and was associated with elevated mortality in one early-planted lowland plantation cohort, where approximately 11% of stems were lost. Combining these realized losses across strata reduced net attributable removal by approximately 11%, to 4.83 Tg C (17.7 Tg CO₂-equivalent), equivalent to a mean annual rate of 1.65 Tg CO₂-equivalent yr⁻¹ over the program period.

Table 2. Program, counterfactual and additionality carbon budget summary, 2011-2023.

Metric	Program observed	Counterfactual baseline	Additionality
Aboveground + belowground carbon stock change (Tg C)	+4.55	-0.86	+5.41
CO ₂ -equivalent (Tg CO ₂ e)	+16.7	-3.2	+19.8
Permanence-adjusted net removal (Tg C / Tg CO ₂ e)	-	-	+4.83 / +17.7
Mean annual permanence-adjusted rate (Tg CO ₂ e yr ⁻¹)	-	-	1.65

Disturbance-adjusted retention, the share of cumulative gross carbon gain still standing at the end of the study period, differed by stratum in a pattern that inverted the accumulation-rate ranking: 89% in the lowland exotic plantation stratum, 95% in the mid-elevation mixed native

stratum, and 97% in the highland assisted natural regeneration stratum. Figure 1 shows the cumulative program and counterfactual carbon trajectories over the full study period, with the additionality gap widening most rapidly during 2018-2023 as the earliest-planted cohorts, established in 2011-2014, reached the steepest portion of their growth curve.

4. DISCUSSION

These results indicate that a substantial share of this program's apparent carbon benefit reflects genuine additionality rather than biomass gain that would have occurred regardless of intervention: the counterfactual stratum's continuing carbon loss meant additionality exceeded gross program carbon gain by roughly a fifth, consistent with the broader finding that additionality assessments on actively degrading land can report larger climate benefit than a before-after comparison of the treated area alone [3,17]. This dependence on a declining counterfactual also means the estimate is only as reliable as the matched-pixel baseline construction, and programs sited on land with a less clearly degrading trajectory should expect a smaller, possibly near-zero, additionality premium over gross gain.

The inverse relationship we observed between accumulation speed and disturbance-adjusted retention, fastest in the exotic plantation stratum, most durable in assisted natural regeneration, echoes concerns raised about monoculture plantation carbon accounting [23] and about the climate risks facing planted and regenerating forest under increasing fire and drought exposure [19]. A program evaluated only on gross early accumulation would rank the lowland plantation stratum as the clear top performer; once permanence losses over even this relatively short 13-year record are included, its advantage narrows substantially, and a longer record encompassing additional harvest cycles or drought events would likely narrow it further, a pattern broadly consistent with the ecological literature on tropical and subtropical secondary forest carbon resilience [6,13].

The comparatively slow but accelerating accumulation observed in the highland assisted natural regeneration stratum is consistent with reports that natural regrowth carbon accumulation is nonlinear, with rates increasing over the first one to two decades as canopy cover and soil conditions recover [2,6,26], and supports the broader case made elsewhere for assisted natural regeneration as a lower-cost, higher-permanence complement to active planting where site conditions and residual seed sources permit it [21,22]. That said, our highland exclosures benefited from active livestock exclusion, a management intervention with its own recurring cost and compliance requirements, so the durability advantage we report should not be read as evidence that regeneration is passive or free of ongoing programmatic input.

Several limitations qualify these findings. First, the matched-pixel counterfactual, while constructed to balance treated and untreated pixels on observable

pre-program characteristics, cannot rule out unobserved confounding, such as differential future protection status or community engagement correlated with program siting, and should be treated as a plausible rather than a definitive baseline [17]. Second, our permanence accounting captures only realized losses within the 13-year study period; it does not project forward fire, drought or pest risk under a warming climate, and studies of climate-driven risk to forest carbon storage suggest such risk is likely to grow rather than remain stable over the coming decades in comparable landscapes [19]. Third, the GEDI-calibrated biomass model, while validated against 214 field plots, was fitted using GEDI data available only from 2019 onward and applied retrospectively to earlier Landsat imagery, so early-period biomass estimates carry additional, not fully quantified, extrapolation uncertainty. Finally, this is a single-program, single-landscape study; accumulation rates, counterfactual dynamics and permanence risk are all likely to vary with regional climate, species selection, and land tenure context in ways this analysis cannot generalize beyond the landscape studied here.

5. CONCLUSION

Combining a 13-year Landsat and GEDI-lidar biomass record with a matched-pixel counterfactual baseline, we estimate that a 215,000 ha regional reforestation program removed 5.41 Tg C (19.8 Tg CO₂-equivalent) of additional carbon relative to the land-use trajectory the program area would plausibly have followed in its absence, of which approximately 89% (4.83 Tg C, 17.7 Tg CO₂-equivalent) remained standing after accounting for realized fire and drought losses through 2023. Accumulation rate and disturbance-adjusted retention were inversely related across intervention types, with fast-growing exotic plantation delivering the largest gross gains but the lowest retention, and assisted natural regeneration delivering the smallest gross gains but the highest retention. These findings support reforestation as a source of genuine, remotely verifiable additional carbon removal, while underscoring that headline sequestration figures reported without an explicit counterfactual baseline and without accounting for realized permanence losses are likely to misstate the net climate benefit actually attributable to a given program.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

W.M. conceived and supervised the study, designed the additionality and permanence analysis framework, and led the writing of the manuscript. J.F. developed the GEDI-Landsat biomass model and performed the remote sensing time series reconstruction. J.P. constructed the matched-pixel counterfactual baseline and performed the field plot calibration and uncertainty analysis. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used publicly available satellite imagery, GEDI lidar data, and forest inventory plot records collected under the program implementing agency's routine monitoring protocols, and did not involve human participants, animal subjects, or procedures requiring ethical review.

Data Availability

Landsat and GEDI biomass data products used in this study are publicly available from their respective originating agencies. Processed carbon stock trajectories, matched-pixel counterfactual datasets, and analysis code supporting the findings of this study are available from the corresponding author on reasonable request.

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