Assessing UAV direct-seeding for tropical forest restoration: early-stage growth and cost-effectiveness

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Running head: UAV direct-seeding for restoration

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Author contributions

GS, EC conceived the ideas and designed the methodology; GS led data analysis, writing, and manuscript revision; with support from MV, LKW for interpretation; EM performed species identification; LKW, JT contributed to manuscript revision; EC supervised writing, analysis, and review; all authors critically reviewed the drafts, approved the final version.

Abstract

Introduction: The high cost, labor intensity, and infrastructure needs of manual tree planting limit the scale of global forest restoration. UAV-assisted direct seeding is a promising alternative, but comparative empirical data are scarce. **Objectives:** This study assesses UAV-assisted direct seeding as a cost-effective alternative to manual planting for tropical forest restoration by comparing early-stage above-ground biomass (AGB) accumulation, species diversity, and cost-effectiveness. **Methods:** Over a 2.5-year period in the Amazon biome, we measured seedling growth and species diversity in UAV-direct-seeded sites. These measurements were compared to a benchmark from manual planting projects using descriptive metrics and statistical testing. Cost-effectiveness was analyzed across three adaptive management scenarios requiring one, two, or three seeding rounds. **Results:** A descriptive comparison showed the median AGB of direct-seeded sites was nearly double that of a benchmark from manually planted projects at 1.5 years, increasing to over threefold at 2.5 years. However, outcomes across the sites were highly variable; estimated species richness (Chao1) ranged from 3 to 29, with natural regeneration comprising the majority of species at the youngest site. In a single-round scenario, direct seeding was 2- to 9-times more cost-effective (based on cost per kg AGB), but this advantage was lost when three rounds were required. **Conclusions:** UAV-assisted direct seeding is a viable method for achieving key ecological outcomes, including rapid biomass accumulation and species diversity, in early-stage tropical forest restoration. However, its success and cost-efficiency are highly dependent on site conditions permitting establishment in a single seeding round. **Implications for Practice:** This study provides evidence that, in suitable contexts, UAV direct seeding can more than double the area restored for the same cost as manual planting. This makes it a powerful addition to the practitioner's toolkit, especially for large or inaccessible areas where manual planting is logistically prohibitive. However, realizing this efficiency requires a holistic ecological approach, encompassing site assessment, species selection, and seeding density, to ensure high establishment success in a single intervention. By dramatically improving the cost-per-hectare, this technology can significantly increase the scale and impact of restoration programs.

Introduction

Tropical forests are among the most biodiverse and productive ecosystems on Earth, serving as critical components of global carbon cycling, climate regulation, and biodiversity conservation (Artaxo et al. 2022). They house more than half of the world's terrestrial species and play a vital role in supporting millions of livelihoods (Saha 2020). Despite their ecological and economic importance, these ecosystems face unprecedented levels of deforestation and land degradation. Over the last decades, tropical deforestation has accounted for roughly 20% of global greenhouse gas emissions, leading to significant ecological and economic losses (Gibbs & Herold 2007).

In response to these challenges, large-scale reforestation and afforestation projects have emerged as essential strategies to combat climate change and biodiversity loss (Bonan 2008). These efforts are increasingly driven by ambitious restoration targets, such as those outlined by the Bonn Challenge and the UN Decade on Ecosystem Restoration, which are supported by high-level political frameworks like the Convention on Biological Diversity (CBD) and the United Nations Framework Convention on Climate Change (UNFCCC). These frameworks emphasize forest restoration as a cornerstone for achieving global biodiversity and climate targets. Moreover, recent studies highlight the co-benefits of reforestation, including enhanced carbon sequestration, improved water regulation, and increased productivity through species diversity (Rosa & Marques 2022).

However, the practical implementation of reforestation at scale is fraught with challenges. Traditional restoration techniques, such as manual planting, require intensive labor and high operational costs (Khoza et al. 2024) and are further constrained by logistical bottlenecks, including the limited availability of nursery-grown seedlings and the infrastructure to produce them at scale (Fargione et al. 2021). Additionally, these methods often involve substantial resource investments, which can pose financial barriers for large-scale projects. To overcome these challenges, innovative and cost-effective approaches are crucial (Werden et al. 2024).

Emerging technologies, among which Uncrewed Aerial Vehicles (UAVs), offer promising solutions to these barriers. UAVs provide substantial utility for restoration planning, implementation, and monitoring at scale, including habitat mapping and wildfire management(Robinson et al. 2022). UAV-assisted direct seeding, has been proposed as a method to rapidly reduce labor costs and increase the scale of reforestation efforts (Stamatopoulos et al. 2024). However, this enthusiasm must be tempered by significant ecological challenges. Critics caution that success rates are often overstated, as broadcasted seeds and young seedlings must overcome numerous well-documented biotic and abiotic obstacles, including seed predation, desiccation, and intense competition, which are often the primary determinants of seedling establishment (Andres et al. 2022; Castro et al. 2023; Souza & Engel 2023). Indeed, evidence of UAV-based restoration intervention success remains scarce, and studies emphasize that effective strategies may require precise seed placement tailored to microhabitats, rather than indiscriminate "mass firing" approaches. We address this knowledge gap by providing new empirical data on the outcomes of UAV-based seeding and comparing these results to benchmark data from traditional manual planting projects in a tropical forest context, offering practical insights into the ecological and economic trade-offs of this emerging technology. Here, we provide an early-stage assessment of UAV-assisted direct seeding by comparing its outcomes to benchmark data from traditional manual planting projects in the northern Amazon forest. Over a 2.5-year period, we evaluated the cost-effectiveness and ecological outcomes of both methods. Specifically, we compared aboveground biomass accumulation of direct seeding to manual planting as a indicator of early vegetation recovery. By combining our field data with a detailed cost analysis of implementation expenses and multi-round intervention scenarios, our primary goal was to determine whether UAV-based direct seeding represents a viable and scalable alternative to manual planting during the critical establishment phase of restoration. Such an evaluation is essential for practitioners and project developers who must balance ecological goals with financial constraints to implement large-scale forest restoration effectively (Golub et al. 2021).

Materials and methods

Study areas

This study was conducted across former mining sites in the northern Amazon biome, specifically in the Brazilian state of Pará and in French Guiana (Figure 1). These sites were selected because they represent common scenarios for restoration in the region: post-industrial landscapes with significant soil degradation where scalable, cost-effective reforestation techniques are urgently needed. For comparison, time-series data on CO2 accumulation were sourced from two manual planting projects, also located within the Amazon biome, to serve as a benchmark for traditional restoration outcomes.

Direct-seeding sites

The direct-seeding projects were carried out on former bauxite (Brazil) and alluvial gold (French Guiana) mining sites. Despite both being in the Amazon, the sites feature distinct climates, with the Brazilian site classified as tropical monsoon (Am) and the French Guianan sites as tropical rainforest (Af). The soils also differ, with the Brazilian site characterized by clay-rich Oxisols and the French Guianan sites by sandy, hydromorphic soils. The restoration approach involved UAV-assisted broadcast seeding, and the species mix for each project included a combination of native trees and leguminous cover crops to facilitate establishment. Table 1 summarizes specific details for each site, including the number of species, fertilizer application, and the number of seeding rounds. The number of seeding rounds was based on adaptive management, where additional rounds were triggered if establishment densities fell below project targets. A comprehensive list of all planted species and their corresponding seeding rates is provided in Supplementary Table S3.

Restoration methods and field data collection

Direct-seeding sites: field sampling

To evaluate the early-stage outcomes of the UAV-assisted direct seeding intervention, we established a chronosequence by conducting field monitoring at project sites of different ages. Data collection occurred at 4, 5, 17, 18, and 30 months post-seeding across these distinct sites. At each monitoring event, data collection was focused on individual seedlings that had resulted from direct seeding and were alive at the time of measurement.

Sampling was performed within multiple 10 x 10 m plots at each site. To ensure an adequate sample size for allometric analysis, plot placement for individual height and diameter measurements was targeted in areas of higher seedling establishment density, as identified from initial UAV imagery. This targeted approach for was distinct from the method used to quantify overall stand density, which was conducted across a wider area via analysis of the high-resolution imagery.

Within each plot, we measured two key allometric variables: total height and stem diameter. For taller saplings (trunk height $>$1.3 m), we measured diameter at breast height (DBH) with a diameter tape and total height with a laser rangefinder. For smaller seedlings, we measured height from the ground to the apical bud and the basal diameter (below the first true leaves) using a caliper. For the FG-1 site, which received seeding interventions approximately one year apart, we distinguished between the older and younger cohorts in the 30-month dataset using a height threshold. This 400 cm threshold was identified via a hierarchical clustering analysis of the height and diameter data as the value that most accurately separated the two age groups.

Manual plantation sites: benchmark data

To provide a comparative benchmark for our direct-seeding data, we sourced time-series data on CO2 accumulation from two Verra-certified Afforestation, Reforestation, and Revegetation (ARR) projects located within the Amazon biome (Verra 2025). Since this benchmark data was provided on an annual basis, we used linear interpolation to estimate the corresponding values at our specific monitoring intervals for a comparison of early-stage growth.

Data analysis

Our analysis involved three main components: estimation and comparison of above-ground biomass (AGB), assessment of species diversity, and a cost-effectiveness analysis of different restoration scenarios. For all ecological analyses, only data from tree species were included; herbaceous cover crops were excluded from biomass and diversity calculations.

Above-Ground Biomass (AGB) estimation

To compare the growth performance of the different restoration approaches, we estimated stand-level Above-Ground Biomass (AGB) per hectare (Mg/ha). This was a two-step process. First, we calculated the AGB for each measured tree using the allometric equation from Ducey et al. 2009:

$$\text{AGB} = 0.0985 \times \text{DBH}^{1.879} \times \text{Height}^{0.7355}$$

This individual-tree biomass was then scaled to a per-hectare metric. To link the potential biomass outcomes to our cost-effectiveness analysis, we used three establishment densities (1300, 550, and 350 seedlings/ha) that represent the range of high, medium, and low densities observed across our field sites. We multiplied the median AGB of seedlings at each time point by these empirically-derived density values. This model was selected primarily for its specific applicability to young trees with thin stems, which constituted the majority of our field-measured individuals. The selected equation does not incorporate wood density, which is a known source of uncertainty in multi-species AGB estimates. This was a necessary trade-off, as widely used pantropical models that include wood density, such as that by Chave et al. 2014, would have excluded most of our seedlings from the analysis since they are calibrated for larger trees and have a minimum diameter threshold (e.g., 5 cm).

Following AGB calculation for each individual, the dataset was cleaned for outliers to ensure data integrity. Using z-scores calculated within each age group, we identified and removed 20 data points (1.76% of the dataset) with a z-score exceeding an absolute value of 3.

Statistical analysis

All data processing and visualization were performed in R (version 4.5.1). We calculated descriptive summary statistics (median, standard error) for above-ground biomass and diversity metrics at each time point. To test whether the AGB per hectare in our highest-density scenario was significantly different from the manual planting benchmark, we performed a one-sample Wilcoxon signed-rank test at the 18- and 30-month time points. To account for the variability in our field data, we generated a bootstrapped distribution ($n=1000$) of our AGB/ha values at each time point, which was then tested against the corresponding benchmark value. Since the benchmark data was only available for integer years, we used linear interpolation to estimate the benchmark AGB values for this comparison. The results of these tests are presented in the Results section.

Diversity analysis

To assess species diversity, we analyzed the community composition for all trees combined, for directly seeded trees only, and for naturally regenerating trees only. For each group, we calculated multiple diversity metrics to provide a comprehensive assessment. These included species richness (S), the Chao1 richness estimator to account for unseen rare species, and Hill numbers ($q=0$, 1, and 2) as a unified framework for measuring diversity (Chao et al. 2013; Jost 2006). All analyses were performed in R using the ‘vegan‘ package (Oksanen et al. 2025). Before calculation, individuals identified as ’Unknown’ (46.5% of the dataset) were excluded. Due to logistical constraints, species-level identification was not performed at the 18-month monitoring site, so no diversity data is available for this time point.

Cost-effectiveness analysis

Plantation cost data

To evaluate the economic feasibility of each restoration method, we first compiled implementation cost data. Costs for UAV-assisted direct seeding were derived from the operational budgets of the projects detailed in this study. These costs include all project stages from initial site diagnosis and planning through seed sourcing and the planting flights themselves, encompassing all direct and indirect expenses such as labor and amortized equipment costs. For a fair comparison, long-term monitoring costs were excluded from this analysis.

Costs for traditional manual planting were sourced from two comprehensive studies to establish a realistic cost range. A survey of projects across Latin America (Cole et al. 2024) provided the upper-end cost estimate, while a study focused specifically on Brazil (Brancalion et al. 2019) provided a more conservative, lower-end estimate. This range of benchmark costs typically includes site preparation, nursery-grown seedling production, manual planting labor, and initial maintenance for 1-3 years until establishment.

Cost-effectiveness metrics

To evaluate the cost-effectiveness of each restoration approach, we analyzed three scenarios for UAV-assisted direct seeding reflecting an adaptive management strategy. These scenarios were based on the initial seedling establishment density: (i) a high-density scenario achieving 1300 seedlings/ha after one seeding round; (ii) a medium-density scenario requiring a second round to reach 550 seedlings/ha; and (iii) a low-density scenario requiring two additional rounds to reach 350 seedlings/ha. The costs for these scenarios were compared against the manual plantation benchmark, which has an average density of 1104 seedlings/ha (Cole et al. 2024). We calculated three distinct metrics: *Cost per established seedling* ($/seedling), calculated as the total implementation cost divided by the final target density; *Cost per kg of AGB* ($/kg AGB), calculated as the total cost divided by the total biomass per hectare at 30 months; and *Diversity per $1000 Spent*, representing the Gini-Simpson diversity index (Simpson 1949) scaled by the total cost. The diversity metric was calculated for the direct-seeding scenarios only, due to a lack of publicly available species-level data for the benchmark projects.

Results

Early-stage biomass and diversity outcomes

A comparison of the direct-seeded chronosequence against the manual plantation benchmark revealed substantial differences in stand-level biomass accumulation (Table 2). While the AGB of the youngest direct-seeded sites was comparable to the benchmark, a performance advantage emerged over time that was statistically significant at the later time points. In the high-density scenario, the median Above-Ground Biomass (AGB) for direct seeding reached 2.74 Mg/ha at 18 months and increased to 13.5 Mg/ha at 30 months, more than double and fourfold the respective benchmark values (Wilcoxon test, $p < 0.001$; Figure 2). These results indicate a rapid acceleration in stand-level biomass accumulation for the direct seeding method after the initial establishment phase.

In addition to biomass, the restoration method successfully established communities of varying species diversity. Estimated species richness (Chao1), which accounts for rare, unsampled species, ranged from 3 at the 5-month site to 29 at the 4-month site. Notably, the composition of this richness also differed across the chronosequence: natural regeneration accounted for the vast majority of species at the 4-month site (24 of 29 species), whereas sown species constituted the majority of richness at the 17- and 30-month sites (see Supplementary Table S4 for full diversity metrics).

Cost-effectiveness analysis

The implementation cost for a single round of direct seeding ($985–$3,088/ha) was consistently lower than the estimates for manual plantation ($5,312–$7,756/ha). This translated into greater efficiency for the single-intervention scenario, where direct seeding cost only $0.07–$0.23 per kg of AGB produced, compared to $0.46–$0.68 for manual planting (Figure 3). This cost-effectiveness advantage diminished as more interventions were required. In the two-round scenario, the cost range for direct seeding ($0.28–$0.97/kg AGB) became comparable to the manual planting benchmark. For the three-round scenario, representing a challenging site, direct seeding was generally less cost-effective, with its cost range ($0.62–$2.20/kg AGB) exceeding that of manual planting. Thus, the economic viability of direct seeding is critically dependent on achieving high establishment success with minimal follow-up interventions. A comprehensive summary of all cost-effectiveness metrics is provided in Table 3.

Discussion

Our findings demonstrate that UAV-assisted direct seeding can be an effective and economically viable method for the critical early stages of tropical forest restoration. This study provides evidence that an initially lagging growth period for direct-seeded seedlings is quickly overcome, leading to significantly greater stand-level biomass accumulation compared to the traditional manual planting benchmark by 18 to 30 months. Critically, this ecological success can be achieved with superior cost-effectiveness, especially in favorable scenarios requiring only a single intervention. Furthermore, our results show that this approach can establish diverse, multi-species communities, fulfilling a primary goal of ecological restoration.

The high costs associated with traditional restoration methods remain a primary barrier to achieving landscape-scale ecosystem recovery (Brancalion et al. 2019; Cole et al. 2024). Intensive site preparation and post-planting maintenance, in particular, contribute to the expense of nursery-based manual planting, even while they aim to ensure reliable outcomes (Löf et al. 2012). The search for more cost-effective strategies is therefore a central goal in restoration science (Crouzeilles et al. 2020; Werden et al. 2024). Our findings position UAV-assisted direct seeding along this continuum of cost-effective alternatives, occupying a crucial middle ground. It is an active restoration technique capable of reintroducing desired species to degraded areas where natural regeneration is unlikely to succeed (Ceccon et al. 2016), but without the high labor costs and reliance on fixed, permanent infrastructure (e.g., large-scale nurseries) associated with manual planting.

However, this cost-effectiveness depends on the intensity of intervention required at a given site. Our analysis, structured around three intervention scenarios, provides a practical framework for understanding the economic implications of ecological risk. The 'single intervention' scenario represents an ideal outcome where biotic and abiotic filters—such as seed predation, desiccation, or intense weed competition (Naruangsri et al. 2024)—are successfully overcome. Conversely, the scenarios requiring two or three interventions model the escalating costs associated with project setbacks. This framework demonstrates that the cost-efficiency of UAV-direct seeding is not guaranteed; it conditional on the success of applying only one round of seeding, which requires careful site selection and seed mix design.

The high variability in ecological outcomes across our sites further underscores this context-dependency. The different growth trajectories do not predict a single, universal path but rather reflect the unique environmental conditions of each project. This is particularly evident in the species diversity results. The high species richness observed at the 4-month site, for example, was overwhelmingly driven by natural regeneration, a likely consequence of topsoil application at that site stimulating the native soil seed bank. Conversely, the low richness at the 5-month site directly reflects its restoration design, where a smaller number of species was initially sown. In contrast, the communities at the later-aged sites (17 and 30 months) were structured differently, with sown species constituting the majority of the richness. This demonstrates that the resulting early community structure is not a product of the seeding intervention alone, but an interplay between the seeding strategy, site management history, and natural ecological processes.

The interpretation of our findings must be framed by several key limitations. Methodologically, the greatest caveat is the lack of a dedicated, paired experimental control group; our comparison relies on publicly available benchmark data from projects with different site histories, species compositions, and management regimes. This means that while our results are compelling, they cannot definitively attribute causality to the restoration method alone. Future work should prioritize multi-site, long-term paired experiments to systematically disentangle these variables. Secondly, our analysis is constrained by the scope of our measurements. It is confined to the early stages of establishment (up to 30 months) and does not capture long-term forest dynamics, which are known to be critical for assessing ultimate restoration success (Reid et al. 2017; Ruiz-Jaen & Mitchell Aide 2005). More specifically, our assessment begins with successfully recruited seedlings at four months and therefore does not directly measure the crucial germination and early survival phase. This initial period represents the greatest bottleneck for direct seeding (Souza & Engel 2023), where success is determined by overcoming ecological filters like poor soil conditions, desiccation, and seed predation. The UAV is an efficient tool for seed delivery, but it does not inherently solve for these ecological filters. This highlights that the technology's success is contingent on its integration into a complete restoration framework that includes careful site assessment and preparation designed to mitigate these early risks. Therefore, while our AGB analysis shows what is possible for survivors, it also underscores that the delivery tool is only one part of a successful restoration strategy. As noted in the methods, our biomass estimates also carry inherent uncertainty due to the omission of wood density, meaning our results are best interpreted as a comparison of woody volume accumulation rather than precise carbon mass. Furthermore, our cost-effectiveness calculations rely on a simplifying assumption that individual seedling AGB is independent of final stand density, which does not account for potential density-dependent competition effects on growth. Finally, the lack of publicly available, species-level data for the benchmark projects prevented a direct comparison of biodiversity outcomes, underscoring a broader need for holistic monitoring standards.

In conclusion, meeting ambitious global forest restoration targets requires a diverse toolkit of innovative strategies. Our study provides robust, data-driven evidence that UAV-assisted direct seeding is a valuable addition to this toolkit. For restoration practitioners, this technology offers a pathway to significantly lower implementation costs and increase the potential scale of projects, particularly for large or inaccessible terrain. However, our findings underscore that this is not a "silver bullet"; its success is highly dependent on a sound ecological strategy that matches the intervention to site-specific conditions, encompassing careful site assessment, species selection, and seeding density. Ultimately, by providing evidence for a cost-effective pathway to achieve critical early-stage restoration goals, this work offers a promising approach to help accelerate the pace and scale of ecosystem restoration worldwide.

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Conflict of interest statement GS, EM, MV, EC are affiliated with a private sector company specializing in direct seeding for tropical reforestation (MORFO). However, this affiliation did not influence the study's design, analysis, or interpretation. No conflicts of interest exist regarding the publication of this work.

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Figures

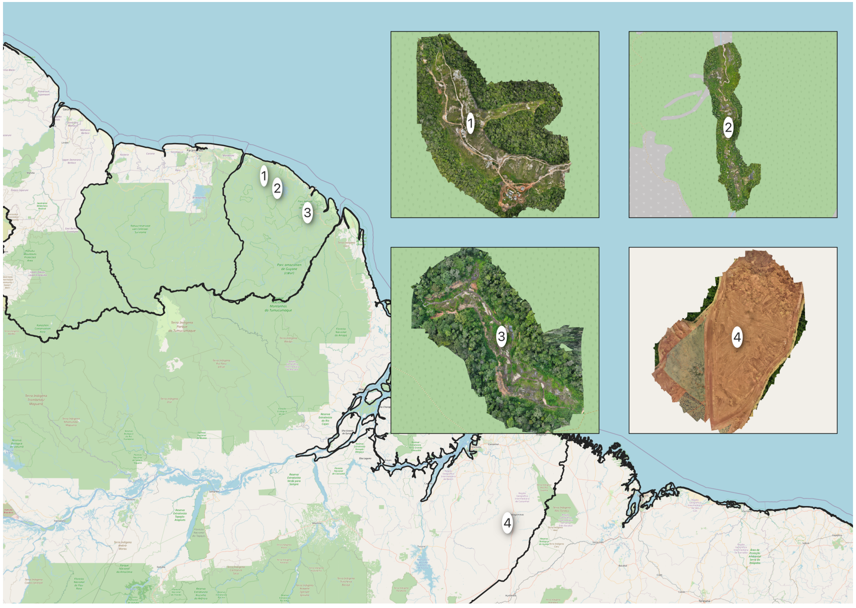

Figure 1: Location and orthophotos of the four different reforestation projects, spanning across northern Brazil and French Guiana.

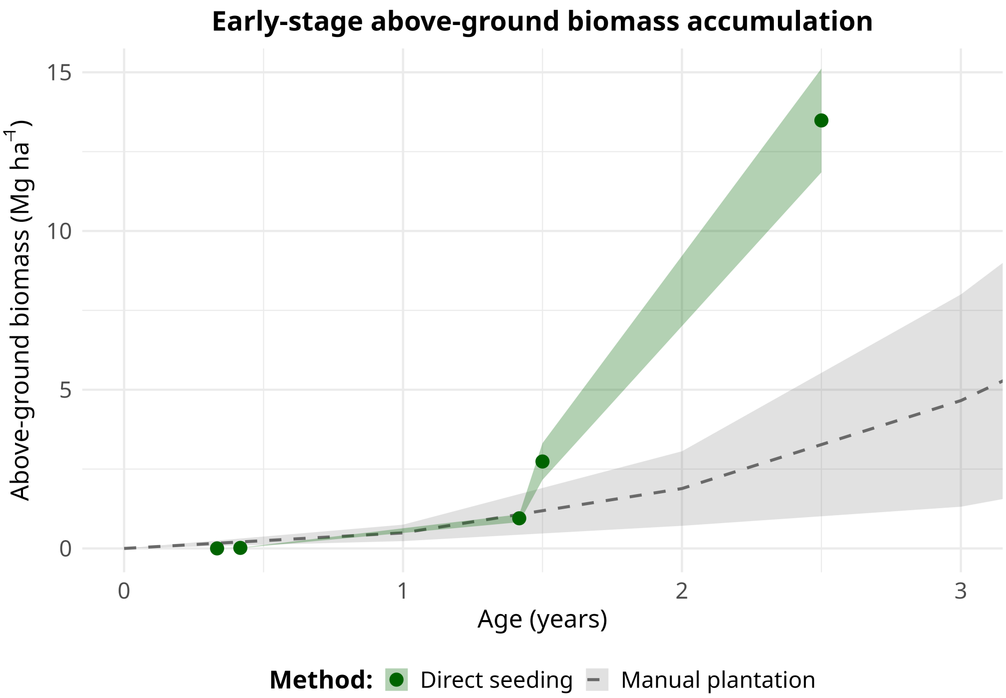

Figure 2: Comparison of early-stage above-ground biomass (AGB) accumulation between direct seeding field data (green points and ribbon showing median ±SE) and a manual plantation benchmark (grey dashed line and ribbon showing mean ±SD).

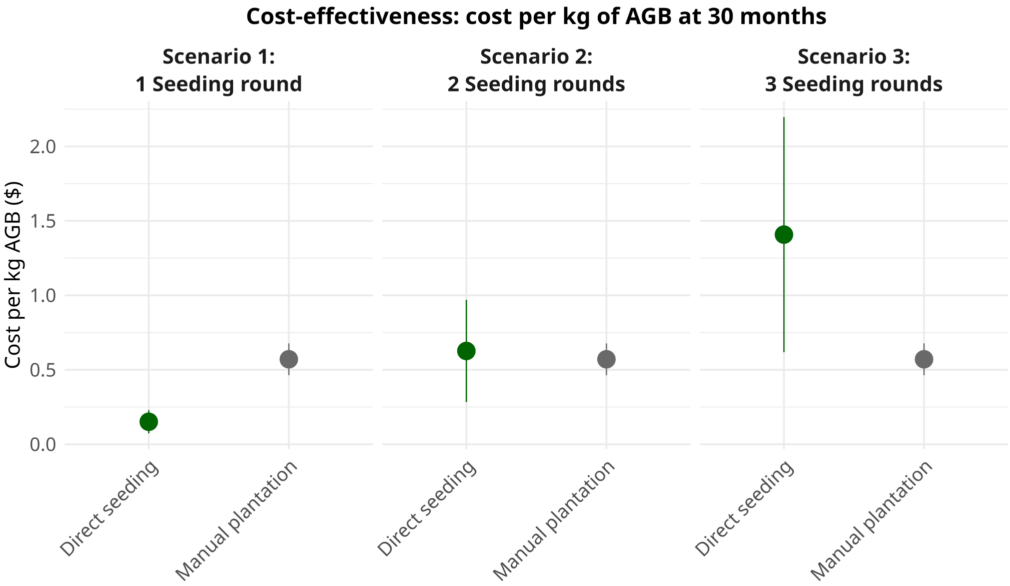

Figure 3: Cost-effectiveness of direct seeding versus manual plantation, measured as the cost to produce one kilogram of AGB at 30 months. Points represent the average of high and low cost estimates, and lines show the full range of estimates for each scenario.

Tables

Table 1: Summary of restoration methods applied at each direct-seeding site.

Site identifier	Tree spp.	Herbaceous spp.	Fertilizer (kg/ha^{-1})	Seeding rounds
Brazil (Paragominas)	11	5	82	1
French Guiana (FG-1, St. Élie West)	37	6	100	Up to 3
French Guiana (FG-2, St. Élie Sandy)	5	4	None	1
French Guiana (FG-3, Regina Central)	14	3	None	1

Note: Species counts reflect the final aggregated list of all unique species seeded across all interventions for each project.

Table 2: Ecological outcomes for direct seeding sites compared to the manual plantation benchmark.

Age (months)	Restoration method	AGB (Mg ha^{-1})	Density (per ha)	Sown Richness	Nat. Regen Richness
4	Direct seeding	0.00	2567.00	5	24
	Manual plantation	0.17	1104.00	NA	NA
5	Direct seeding	0.02	760.00	1	2
	Manual plantation	0.21	1104.00	NA	NA
17	Direct seeding	0.95	2041.00	8	3
	Manual plantation	1.07	1104.00	NA	NA
18	Direct seeding	2.74*	1750.00	NA	NA
	Manual plantation	1.19	1104.00	NA	NA
30	Direct seeding	13.5*	2041.00	7	2
	Manual plantation	3.27	1104.00	NA	NA

Note: Direct seeding AGB is the median value from the high-density scenario. Manual plantation AGB is the mean value interpolated from Verra Registry data. Density for direct seeding is the observed field value; benchmark density is the reported average. Richness is the Chao1 estimated value. * indicates a statistically significant difference ($p < 0.01$) from the benchmark based on a Wilcoxon signed-rank test on AGB/ha.

Table 3: Comprehensive cost and cost-effectiveness analysis across three restoration scenarios.

Scenario	**Method**	**Cost ($/ha)**	**$/seedling**	**$/kg AGB**	**Diversity per $1000**
Scenario 1	DS range	985 – 3,088	0.76 – 2.38	0.07 – 0.23	0.23 – 0.72
(1 seeding round)	Manual range	5,312 – 7,756	4.81 – 7.03	0.46 – 0.68	Not available
Scenario 2	DS range	1,615 – 5,531	2.94 – 10.06	0.28 – 0.97	0.13 – 0.44
(2 seeding rounds)	Manual range	5,312 – 7,756	4.81 – 7.03	0.46 – 0.68	Not available
Scenario 3	DS range	2,246 – 7,974	6.42 – 22.78	0.62 – 2.20	0.09 – 0.31
(3 seeding rounds)	Manual range	5,312 – 7,756	4.81 – 7.03	0.46 – 0.68	Not available